91602
new 82-10

ontario hydro
research division

SHAFT BACKFILL STUDY: HIGH-PRESSURE COMPRESSION CELL AND PRELIMINARY DATA

Report No 90-129-K

H.T. Chan, Senior Engineer
K.C. Lau, Engineer
Soil Sciences Section
Civil Research Department

ABSTRACT

A high-pressure compression cell with a maximum allowable applied pressure of 7 MPa, was designed and constructed for performing compression tests on compacted, swelling and nonswelling clay-based specimens. The testing program was part of a comprehensive study on the properties of shaft backfill related to the interactions between the backfill and the host rock. The report first summarizes the work done on shaft backfill by Civil Research staff in the past few years. It then describes in detail the design and calibration of the high-pressure compression cell. Some preliminary compression test results are also presented.

job	file	date	report no.
43-110-061	843.2	September 13, 1990	90-129-K

91-03156/

TABLE OF CONTENTS

	Page
1.0 INTRODUCTION	1
2.0 BRIEF REVIEW OF PREVIOUS STUDIES	2
3.0 THE HYDRAULIC COMPRESSION TEST EQUIPMENT	6
3.1 The Main Chamber	6
3.2 The Pressure Supply Chamber	9
3.3 Monitoring System	9
4.0 SAMPLE PREPARATION	10
5.0 TEST PROCEDURES	11
5.1 De-airing of the System	11
5.2 Placement of Backfill Sample	12
5.3 Installation of the LVDT	12
5.4 Application of Hydraulic Load	12
6.0 DEFORMATION MEASUREMENT CALIBRATION	13
7.0 PRELIMINARY TEST PROGRAM	14
8.0 DISCUSSION AND CONCLUSIONS	16
REFERENCES	18
FIGURES 1 TO 27	19
APPENDIX A	45
DISTRIBUTION	last page

90-129

ontario hydro
research division

To: Mr. D.W. Souther
Manager, Nuclear Engineering Department
Design and Development Division - Generation

Attn: Dr. S.J. Naqvi

**SHAFT BACKFILL STUDY:
HIGH-PRESSURE COMPRESSION CELL
AND PRELIMINARY DATA**

1.0 INTRODUCTION

In the proposed Canadian design of an underground repository for nuclear spent fuel, effective isolation of the radionuclides in the geosphere must be ensured for tens of thousands of years. Therefore, after the placement of the wastes, the shafts, drifts, boreholes and disposal vaults that form, the repository must be adequately sealed in such a way that they do not constitute easy pathways for the movement of radionuclides/1/. In the proposed design, the shafts would be backfilled with a compacted clay-based material, probably a mixture of clay and/or crushed granite. Arching action between the soil backfill and the host rock may reduce the vertical soil pressure significantly. Consequently, there may be little horizontal soil pressure acting against the host rock. When the disposal vault is closed, the dewatering system for the vault will be disconnected resulting in a significantly increased pressure from the redistributed groundwater around the vault. At great depths, groundwater pressure at the backfill/rock interface may be quite high. Hydraulic pressure will cause compression of the clay-based backfill and, depending on the compression characteristics of the backfill, a small annulus gap may develop between the backfill and the wall of the shaft and form a possible short circuit path for the migration of radionuclides from the vault to the biosphere. The magnitude and the rate of self-healing of these gaps are also determined by the characteristics of the backfill mix. This gap must be eliminated prior to the release of radionuclides from the waste containers.

To study the behaviour of backfill mixes subjected to hydraulic loading, research programs were conducted from 1982 to 1986 and from 1988 to the present. In the more recent study, a high-pressure compression cell was designed and built at Ontario Hydro's, Research Division to examine the deformation behaviour of backfill mixes subjected to a large hydraulic loading.

This report briefly reviews some related studies conducted in the Civil Research laboratories in the last several years. A description of the design and construction of the high-pressure (up to 7 MPa) compression cell used in the present study follows, including reports of test data and their interpretation.

2.0 BRIEF REVIEW OF PREVIOUS STUDIES

It is postulated that along the axis of the shaft, the vertical pressure in the backfill increases less rapidly than the total weight of the backfill due to the development of the shearing resistance between the backfill and the shaft wall and as such, the vertical pressure will approach asymptotically a finite value. A simplified analytic solution for the vertical pressure distribution was developed in the initial phase of this program to predict the pressure distribution of a shaft backfill/2,3/. Theoretically, the effective vertical pressure (σ'_v) and horizontal pressure (σ'_h), can be calculated by the following equation.

$$\sigma'_v = \frac{1}{A}\left[\gamma - \frac{2}{Fa}\left(c'_a + P_{s(h)}\tan\delta - u_o k_o \tan\delta\right)\right]\left(1-e^{-Az}\right) - u_o$$

$$A = \frac{[2k_o\tan\delta(1-B)]}{Fa}$$

$$\sigma'_h = \sigma'_v \cdot k_o$$

z = depth
u_o = pore-water pressure
a = radius of the shaft
$\tan\delta$ = frictional coefficient between backfill and shaft rock-wall surface
c'_a = adhesion at the interfacial zone
γ = unit weight of backfill
$P_{s(h)}$ = horizontal component of swelling pressure
k_o = earth pressure coefficient at rest
B = pore pressure coefficient
F_a = shearing mobilization factor

In 1985, following development of the equations for calculating the distribution of the vertical and horizontal pressures in the shaft backfill, laboratory tests were carried out to measure the horizontal pressures in two shaft models. The collected experimental data were compared with the theoretic calculations.

The dimensions of the two model shafts are shown in Figure 1. Three pressure transducers were used to measure the horizontal pressure exerted by the backfill on the inner wall surface of the model.

Variations of the measured horizontal pressure with depth were compared with the theoretic pressure distribution (Figures 2 and 3). In the computations, a range of reasonable values for earth pressure coefficient at rest (k_o) and frictional coefficient between backfill and shaft rock-wall surface ($\tan\delta$) was assumed for the loose sand. The following conclusions may be drawn from these data:

1) The horizontal pressures are less in the 152.4 mm diameter shaft model than in the 304.8 mm shaft model because of the greater shearing resistance developed between the sand and the smaller diameter shaft.

2) The increase of horizontal pressure with increased depth is much less than that estimated for the "no soil arching" case (i.e. no shearing resistance developed between the soil and the shaft).

3) The experimental observations were similar to predicted results.

The above tests were repeated for a Sealbond (a clayey soil) material. Figure 4 shows the comparison between the measured horizontal pressures and the theoretic calculations. The soil parameters (c'_a and $\tan\delta$) were obtained from direct shear tests on Sealbond sliding against a steel plate surface. The assumed values of k_o and F_a used in the calculations were considered reasonable for the test conditions. The following observations can be made from the results presented:

1) The measured pressures were the "total pressure" (sum of interparticle pressure and pore-water pressure) and their values were much lower than the horizontal pressures estimated for the "no soil arching" case (i.e. no shear resistance developed between the soil backfill and the shaft surface).

2) The difference between the measured pressure and the theoretic pressure was greater than anticipated. However, a small value of pore-water pressure (not measured in this experiment) subtracted from the measured pressures would result in the experimental and theoretic results comparing more closely.

Figure 5 illustrates a comparison between experimental data and theoretic calculations in the 304.8 mm diameter shaft model. The soil parameters (c'_a and $\tan\delta$) were obtained by shearing a Sealbond specimen on a PVC plate. Again, the pressure measurements show horizontal pressures substantially lower than those in the "no soil arching" case.

The experimental study described above has shown that with the shearing resistance developed between the backfill and the shaft model, horizontal pressure due to the weight of the backfill is greatly reduced. The results of these experiments suggest that there is little contact pressure between the backfill and the shaft rock. As a result, during the groundwater recharging phase, the hydraulic pressure at the interface of backfill and rock could cause undesirable compression of the backfill and hence lead to the potential development of a gap at the interface.

An apparatus was designed and constructed in 1984-85 to investigate the lateral compression of compacted clay-based specimens that are subject to hydraulic pressure (Figures 6 and 7).

The main purpose of this experimental program was to demonstrate, under laboratory conditions, whether or not a gap would develop between a compacted soil specimen and the porous liner at a certain hydraulic pressure. Three groups of backfill specimens were used: 1) calcium (Pembina) bentonite mixed with crushed granite compacted to a dry density of about 1.5 Mg/m^3, 2) calcium (Pembina) bentonite mixed with crushed granite compacted to a dry density ranging from 1.57 to 1.77 Mg/m^3, and 3) calcium (Pembina) bentonite and sodium (Avonlea) bentonite mixed with crushed granite compacted to a dry density from 1.57 to 1.63 Mg/m^3.

The laboratory hydraulic compression tests demonstrated that a poorly-compacted clay-based backfill specimen could easily be compressed hydraulically to the extent that a gap would develop at the interface of the specimen and the porous liner. However, when the same backfill specimen was compacted to a higher density or when sodium bentonite (swelling clay) was added to the mixture and compacted to a given minimum density, no gap was observed at the specimen/porous liner interface for a maximum applied water pressure of about 2400 kPa.

The attention of engineers designing the shaft backfill was drawn by these laboratory data to the potential undesirable effect of recharging groundwater pressure on the compressible clay-based material.

Because of limitations of the hydraulic compression cell (see Figure 7), it was not possible by utilizing the radial compression test to measure the magnitude of the gap formed or the rate of rebound of the specimen. Therefore, in a subsequent phase of the shaft backfill project initiated in 1988, a one-dimensional, high-pressure (maximum 7 MPa) compression cell was constructed to study the compression/rebound behaviour of a number of compacted clay-based specimens.

3.0 THE HYDRAULIC COMPRESSION TEST EQUIPMENT

To study the deformation behaviour of compacted clay-based backfill specimens subjected to a large hydraulic loading, a special laboratory test apparatus consisting of three main components; the main chamber, the pressure supply chamber, and the monitoring system (Figure 8), was designed and constructed in Ontario Hydro. A backfill specimen located in the main chamber was hydraulically loaded by pressurized water from the pressure supply chamber. The deformation of the specimen was measured by a linear variable differential transducer (LVDT) and the induced pore-air and pore-water pressures in the specimen were measured by pressure transducers. These sensors were monitored by a data acquisition unit and the data collected were stored in a computer. The design and function of the various components of the equipment are described in the next section and the detail design drawings are presented in Appendix A.

3.1 The Main Chamber

The main chamber consisted of a stainless steel cylinder 155 mm (6-1/8") diameter by 89 mm (3-1/2") high and removable top and bottom caps 13 mm (1/2") thick. Two stainless steel collars, each with 16 evenly spaced threaded holes were welded to the top and bottom of the cylinder (Figure 9). The top and bottom caps were fastened to the cylinder through the collars with bolts. A specially designed o-ring seal was provided in each cap to ensure proper sealing of the chamber (Appendix A, Figures A3 and A4). The maximum allowable design load of the chamber was 7 MPa (1000 psi). It was proof loaded to 10 MPa (1500 psi). The chamber was protected from over-pressure by a pressure relief valve located on the top cap (Figure 10). The relief pressure was set to 8.3 MPa (1200 psi).

The surface deformation of the specimen was monitored by an LVDT mounted on the top cap. Because of the high pressure involved, the LVDT was seated in a specially designed coning tower (see Figure 10).

To simulate the most critical loading, the full hydraulic loading had to be applied to the specimen in a relatively short period. Pressurized water from the pressure supply chamber was forced into the main chamber by opening the valve along the 9.5 mm (3/8") stainless steel tube connecting the chambers (Figure 8). The air within the main chamber, displaced by the water, escaped through a vent located on the top cap of the chamber (see Figure 10). When water filled the main chamber, the air vent was closed and the water pressure within the main chamber increased to the value set by the pressure regulator.

During the application of the hydraulic loading, water forced into the main chamber at high velocity could have caused erosion of the surface of the specimen. Therefore, to ensure full protection of the specimen from the water jet and free access of water to the specimen, a 100 mm (4") diameter 6 mm (1/4") thick coarse carborumdum disk placed on top of a 150 mm (6") diameter perforated aluminum plate was used to deflect the high velocity water jet away from the specimen avoiding direct impact of the water jet on the surface of the specimen (Figure 11).

In the bottom of the main chamber are two recesses, each of which accommodates a stainless steel holder complete with o-ring. A 25 mm (1") diameter by 6 mm (1/4") thick 1.5 MPa (15 bar) porous stone was attached to one of the holders by a ring of epoxy, allowing water to pass completely through the stone. A 28 mm (1-1/8") diameter by 6 mm (1/4") thick 0.2 MPa (2 bar) porous stone was attached to the second holder (Figure 12).

The base of each stone was connected by means of a duct through the main chamber and then through a stainless steel tube to a manifold (Figure 13). Each manifold had two pressure transducer mounting ports. By mounting two pressure transducers of different pressure ranges to the manifold, the pressure in the chamber could be monitored with a transducer of the proper range.

The deformation of a hydraulically loaded clay-based specimen was caused by the simultaneous occurrence of both compression and swelling of the specimen. To better understand the deformation processes, the relative significance of the two components had to be delineated. By isolating the water supplied from the specimen with a neoprene membrane, the deformation of the specimen due to swelling could be eliminated. This type of test was defined as "dry" test. The component of deformation caused by swelling of the specimen could be obtained by performing an identical test without the neoprene membrane (the "wet" test). The component of deformation due to swelling of the specimen was equal to the difference in deformation between the two tests.

A special expandable ring with an o-ring seal was designed to provide a seal for the neoprene membrane (Figure 14). By expanding the ring against the wall of the chamber, a seal was formed between the wall and the neoprene membrane such that the specimen was isolated from the water in the chamber due to the hydraulic load (Figure 15). The equipment shown in Figure 16 was designed and constructed to minimize the effort required to install the neoprene membrane and the expandable o-ring seal.

3.2 The Pressure Supply Chamber

The pressure supply chamber, a stainless steel cylinder 155 mm (6-1/8") diameter and 210 mm (8-1/4") high with removable top and bottom caps, was connected to a bottled nitrogen tank. The pressure witnin the chamber was controlled by a pressure regulator located at the outlet of the nitrogen tank. A water reservoir was connected to the pressure supply chamber through a 9.5 mm (3/8") stainless steel tube. The chamber was proof loaded to 10 MPa (1500 psi). A pressure relief valve installed at the top cap was set to 8.3 MPa (1200 psi). The pressure within the pressure supply chamber was monitored by a pressure transducer located along the stainless steel tube connecting the main chamber and the pressure supply chamber (see Figure 8). The pressure transducer was connected to a data acquisition system.

3.3 Monitoring System

The pore-air and pore-water pressures at the base of the specimen and the hydraulic loading applied to the specimen were monitored by three pressure transducers. The transducers were powered and read by a Digitron Model P300 readout unit. The vertical deformation of the specimen was monitored by a Shaevitz LVDT connected to a readout unit by the Aries Instrument Ltd. In order to automate the monitoring system, a Wykeham Farrance WP12731 digital display unit was used as an interface between the readout units and a laptop computer. The Lab Tech Note Book software was used to perform the data acquisition. During a test, a real time graphic plot of the measured values of the sensors was displayed on the computer monitor.

4.0 SAMPLE PREPARATION

One of the objectives of this study was to determine the deformation behaviour of various backfill mixes under hydraulic compression loading. This deformation behaviour of various backfill mixes will be used to aid the selection of a reference backfill material. In this study, both swelling and nonswelling type clay-based backfill mixes were tested in the high-pressure compression cell. The clays used were the Avonlea bentonite and the Sealbond clay.

The crushed granite used in this study was produced from excavated rock obtained from a quarry near Lac du Bonnet, Manitoba. The particle-size-distribution curves of all the materials tested are shown in Figure 17. The crushed granite used in this study was similar to the crushed granite used for the reference buffer mix. The maximum grain size of the crushed granite was 2 mm.

The crushed granite and the clay at its initial moisture content were blended together in a Hobart mixer. With the proper blending of the crushed granite and the clay, water was added to the mix with a plant sprayer. The mixing continued until a uniform mix was achieved. Depending on the clay type and the required final moisture content, the average mixing process was about 1/2 hour.

After mixing, the material was stored in a sealed plastic bag, and allowed to sit in a moisture room for approximately a week to allow the moisture within the sample to equilibrate prior to testing. The moisture content of the mixture was checked periodically to verify the moisture content of the sample.

5.0 TEST PROCEDURES

The deformation behaviour of backfill mixes subjected to hydraulic loading were studied by testing the samples in the compression cell. The test procedure involved four steps, de-airing of the system, placement of backfill sample, installation of the LVDT, and application of hydraulic load.

5.1 De-airing of the System

For accurate monitoring of the dynamic pore-water pressure response of the specimen, the pore-water pressure monitoring system had to be de-aired properly. By filling the main chamber with de-aired water and opening all the valves in the pressure monitoring manifolds, all entrapped air within the system was drained with the flowing water. When the system became saturated, all the valves in the manifolds were turned off. Opening one of the valves in the pressure transducer mounting ports at the manifold allowed the water level within the port to rise and eventually overflow (Figure 18). The pressure transducer was then mounted on the mounting port without entrapping any air in the system. The transducer was secured to the manifold by tightening the fittings.

De-airing of the porous stones was achieved by boiling the stones in water in a tin foil container for 1/2 hour. Then, to prevent desaturation during transportation from the tin foil container to the main chamber, the porous stones and the tin foil container were submerged in the water in the main chamber. The stones were then pushed into their final positions in the chamber (see Figure 12). During the positioning of the stones, the drainage valves at the pressure transducer manifold were opened to release the pressure building up within the system. Once the stones were properly positioned, the valves at the manifolds were closed.

5.2 Placement of Backfill Sample

The backfill mix was placed in the main chamber in one lift. The sample was spread evenly (Figure 19) and then tamped gently with a steel platen 154 mm (6-1/16") diameter and 19 mm (3/4") thick to ensure levelling of the sample surface (Figure 20). A filter paper was then placed between the platen and the sample. The sample was statically compacted with the hydraulic jack shown in Figure 21. The desired density of the sample was achieved by compressing the sample to a predetermined thickness.

5.3 Installation of the LVDT

After compaction of the specimen and installation of the water deflection assembly in the main chamber, the main chamber was closed off by fastening the top cap to the chamber with bolts. The LVDT was mounted on the chamber by screwing the coning tower onto the top cap (Figure 22). The LVDT was then connected to the data acquisition unit.

5.4 Application of Hydraulic Load

The valve between the pressure supply chamber and the water supply reservoir was opened to allow the pressure supply chamber to fill with water then the valve was closed. A pressure of 150 kPa (21 psi) was then applied to the pressure supply chamber through the nitrogen tank by adjusting the pressure regulator. The valve between the pressure supply chamber and the main chamber and the air vent at the main chamber were opened and pressurized water from the pressure supply chamber flowed into the main chamber. Air in the main chamber was displaced by the influx water and escaped through the air vent. When the chamber was filled,

water overflowed out of the chamber through the air vent. By closing off the air vent, the main chamber was pressurized. The hydraulic pressure was adjusted to meet the requirements of the test by means of the pressure regulator at the nitrogen tank.

The pressures and LVDT readings were monitored by the data acquisition system. The measured pore pressures and the displacement values were plotted on the computer monitor and the data were stored in the computer for future analysis.

6.0 DEFORMATION MEASUREMENT CALIBRATION

During a test, the deformation of the specimen was measured by the LVDT unit. The deformation values measured included the deformation of the specimen and the elastic deformation of the main chamber due to the applied hydraulic loading. To obtain deformation measurements of the specimen alone, it was necessary to determine the relationship between the elastic deformation of the chamber and the applied hydraulic loading. By applying hydraulic loads to the chamber without any soil specimen, the elastic deformations of the chamber and the corresponding applied hydraulic loads could be measured by the LVDT and pressure transducer respectively. The plotted relationship between the chamber's deformation and the applied hydraulic loads is shown in Figure 23. The results indicated that the deformation of the chamber was directly proportional to the applied loading. The ratio was equal to 0.036 mm/MPa. This correction factor was applied to all the measured LVDT results.

7.0 PRELIMINARY TEST PROGRAM

In order to debug the high-pressure compression test equipment and to develop testing procedures for the equipment, both "dry" and "wet" types of high-pressure compression tests were performed on two clay-based backfill mixes. The first clay-based backfill mix was a swelling type Avonlea bentonite clay produced by Avonlea Mineral Industries. The second mix was a nonswelling Sealbond clay. The compacted sample had a thickness of one centimeter.

The swelling type clay-based mix was 25% by weight of Avonlea's bentonite clay and 75% by weight of crushed granite. The initial moisture content of the specimen was 15% and the dry density was 1.7 Mg/m^3. The specimen had a degree of saturation of 75%. The vertical displacement and the changes in pore pressure of the specimen, obtained from the "wet" test, were plotted as shown in Figures 24 and 25. The vertical deformation of the specimen measured from the "dry" test was 0.5 mm, similar to the initial vertical deformation measured from the "wet" test.

The nonswelling clay-based backfill mix was a Sealbond clay with a moisture content of 18%. The dry density of the mix was 1.78 Mg/m^3 at 94% saturation. The vertical deformation and the changes in pore pressure of the specimen measured from the "wet" test were plotted as shown in Figures 26 and 27.

For the swelling clay-based backfill mix, the vertical displacement versus time curve shown in Figure 24 indicates that the initial deformation of the specimen due to the application of the hydraulic loading was 0.55 mm. Because of the fast loading rate, negligible deformation due to swelling of the specimen occurred during the initial loading phase of the test. This finding was substantiated in that vertical deformation values measured from the "dry" test were almost

equal to initial vertical deformation values measured from the "wet" test. With time, swelling of the specimen occurred and 24 hours after the start of the test, the height of the specimen had increased approximately 2.5 mm (25%).

At the base of the specimen, an initial suction of 50 kPa was measured. With the application of the hydraulic loading, the pore pressure within the sample increased immediately to 1 MPa and then equilibrated to a value equal to the applied hydraulic loading.

For the nonswelling clay-based backfill mix, the vertical displacement versus time curve shown in Figure 26 indicates an immediate 0.52 mm compression of the sample due to the applied hydraulic loading. The vertical rebound of the specimen equilibrated at 0.64 mm (0.12 mm above its original level). This measurement was marginally larger than the elastic rebound measurement, 0.45 mm, of the specimen from the "dry" test. At present, this excess amount of vertical deformation is considered to be caused by the release of the locked-in stresses within the specimen.

Because of the high initial degree of saturation of the specimen, the measured initial pore pressure of the specimen was equal to atmospheric pressure. During the application of the hydraulic loading, the pore pressure at the base of the specimen responded immediately to the applied hydraulic loading (see Figure 27).

8.0 DISCUSSION AND CONCLUSIONS

The results of the preliminary testing program have indicated that the high-pressure compression test equipment performed as designed. It is expected that this equipment will be valuable for the assessment of the performance of shaft backfill when specimens are subjected to large hydraulic loading. It will also provide data for the development and calibration of an analytic model to study the compression characteristic of shaft backfills.

The results of the high-pressure compression tests performed on the swelling-type clay-based backfill specimens indicate that an initial compression of the backfill occurred. With time, the specimen swelled and there was a 25% increase in thickness of the specimen within 24 hours.

For the nonswelling-type clay-based backfill specimens, compression occurred due to hydraulic loading. This initial compression of the specimen was larger than the elastic rebound of the sample. With time, a further rebound of the specimen occurred and the final thickness of the specimen was 1.5% larger than its original thickness. This additional rebound of the specimen is considered to be caused by the release of the locked-in stresses within the specimen. The magnitude of the rebound may depend on the compaction method used and, conservatively, it should not be considered in the design of the shaft backfill.

ACKNOWLEDGMENTS

The writers would like to thank Mr. Bob Watts who set up and calibrated the high-pressure compression cell, performed the compression tests, and provided valuable suggestions on the design of the experimental apparatus.

Mr. Nobby Miura of the Mechanical Research Department designed the high-pressure compression cell with specifications from Civil Research staff. His contributions to this experimental study are appreciated.

The project was funded partially by the Nuclear Engineering Department of Ontario Hydro.

Approved by:

T.J. Carmichael

for T.W. Klym
Manager
Civil Research Department

Prepared by:

H.T. Chan

H.T. Chan
Senior Engineer
Soil Sciences Section

K.C. Lau
Engineer
Soil Sciences Section

Reviewed by:

T.J. Carmichael

T.J. Carmichael
Supervising Engineer
Soil Sciences Section

HTC/KCL:LM

REFERENCES

(1) LOPEZ, R.S., S.C.H. CHEUNG and D.A. DIXON, "The Canadian Program for Sealing Underground Nuclear Fuel Waste Vaults", Canadian Geotechnical Journal, Vol. 21, No. 3, pp 593-596, 1984.

(2) MORTAZAUI, M.H.S., H.T. CHAN and H.S. RADHAKRISHNA, "Design Considerations for Sealing the Shafts of a Nuclear Fuel Waste Disposal Vault", Ontario Hydro Research Division Report No. 85-13-K, May 3, 1985.

(3) CHAN, H.T. and H.S. RADHAKRISHNA, "Hydraulic Compression of Shaft Backfill at the Backfill/Rock Interface", Ontario Hydro Research Division Report No. 86-283-K, Nov. 28, 1986.

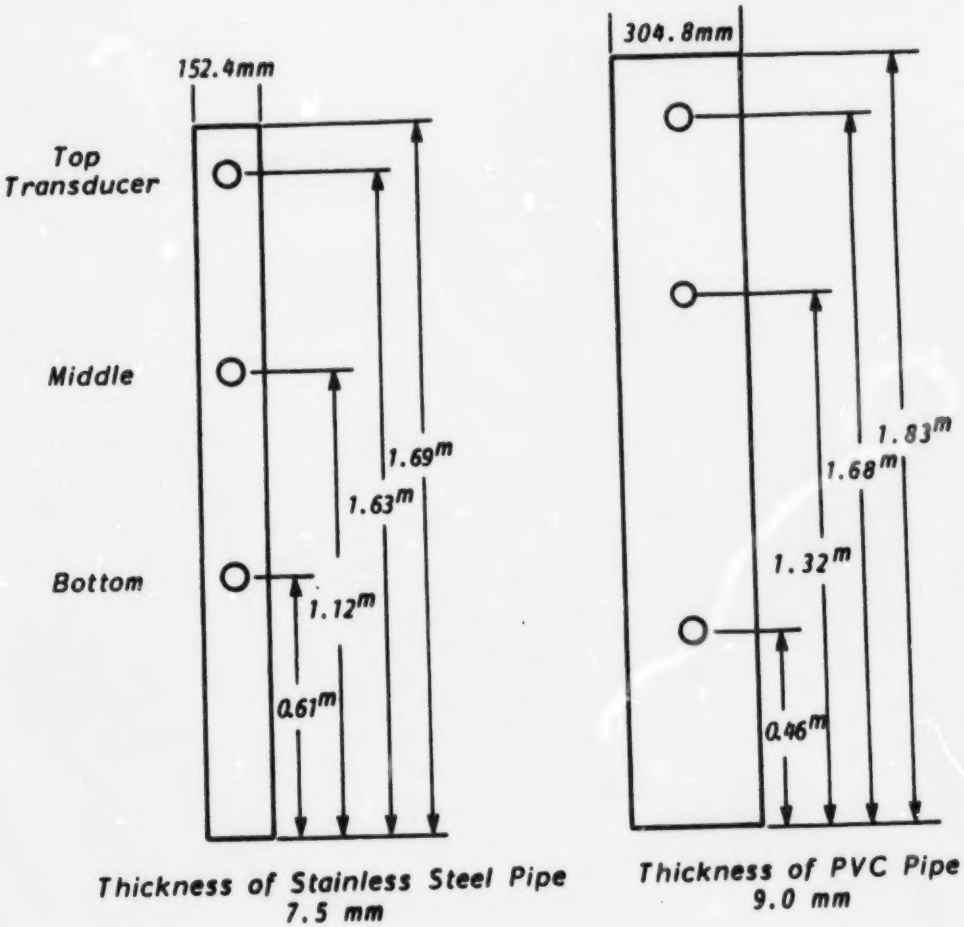


Figure 1 Dimensions of two circular model shafts with locations of transducers shown.

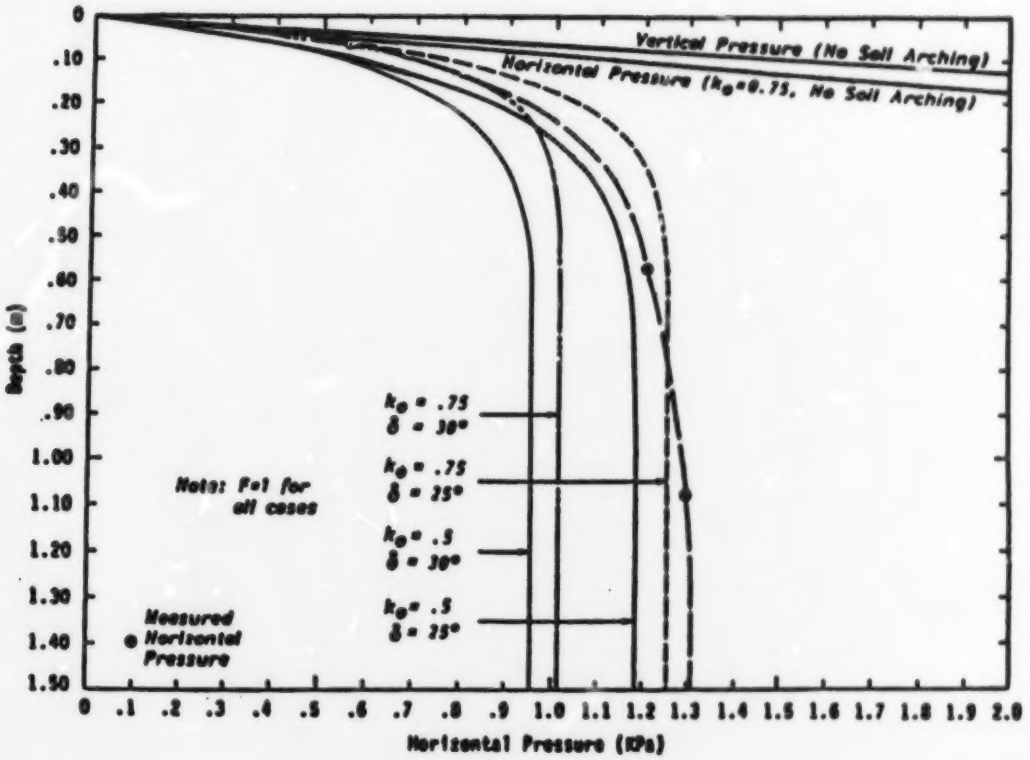


Figure 2 Comparison of measured backfill horizontal pressures in the 152.4 mm dia. model shaft with calculated results. Bulk density of the dry silica sand (backfill) = 1575 kg/m ^{3}

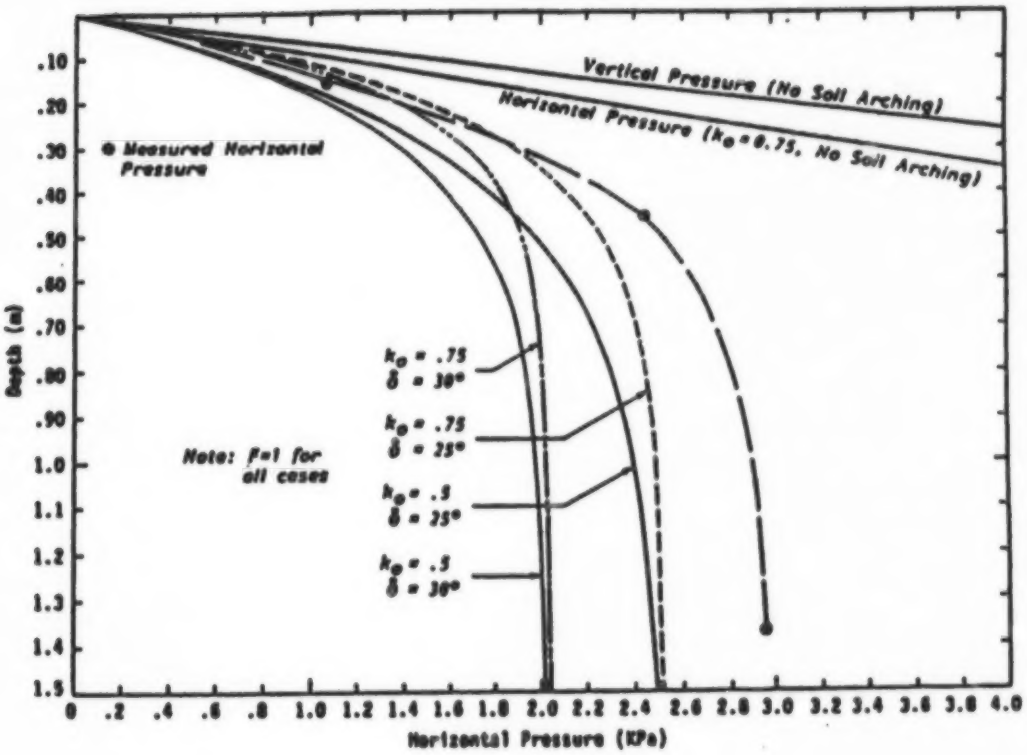


Figure 3 Comparison of measured backfill horizontal pressures in the 304.8 mm dia. model shaft with calculated results. Bulk density of the dry silica sand (backfill) = 1575 kg/m ^{3}

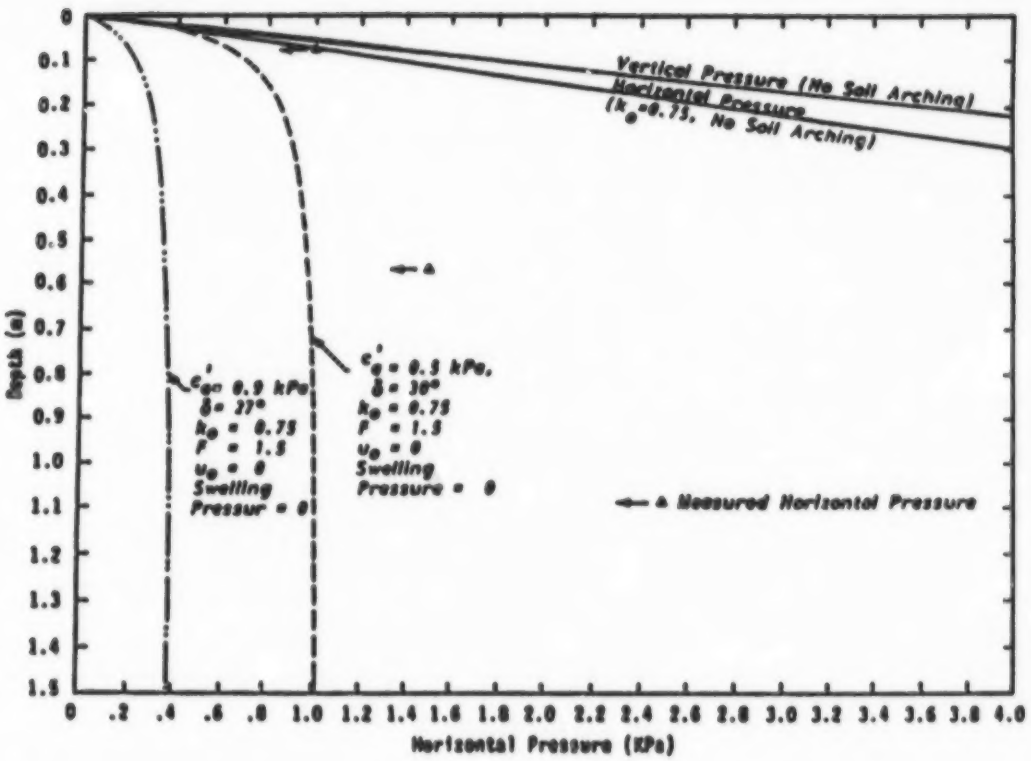


Figure 4 Comparison of measured backfill horizontal pressures in the 152.4 mm dia. model shaft with calculated results. Bulk density of Sealbond (backfill)= 1935 kg/m ^{3} at 25% water content.

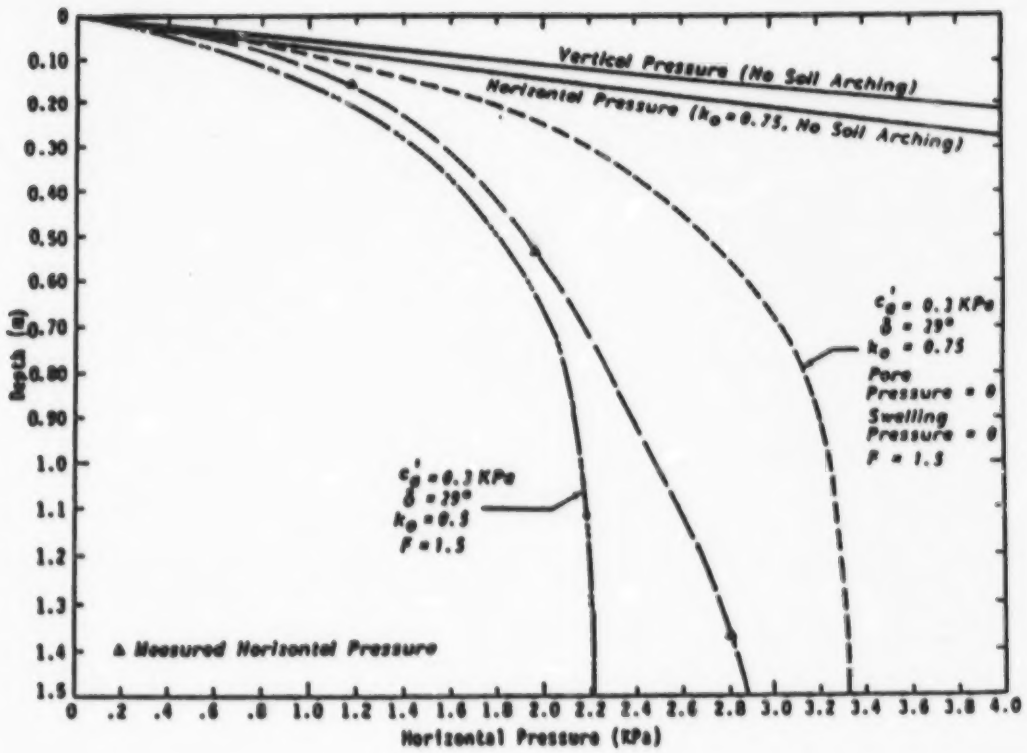


Figure 5 Comparison of measured backfill horizontal pressures in the 304.8 mm dia. model shaft with calculated results. Bulk density of Sealbond (backfill)= 1911 kg/m ^{3} at 25% water content.

Figure 6 Various parts of the cell used for hydraulic compression tests.

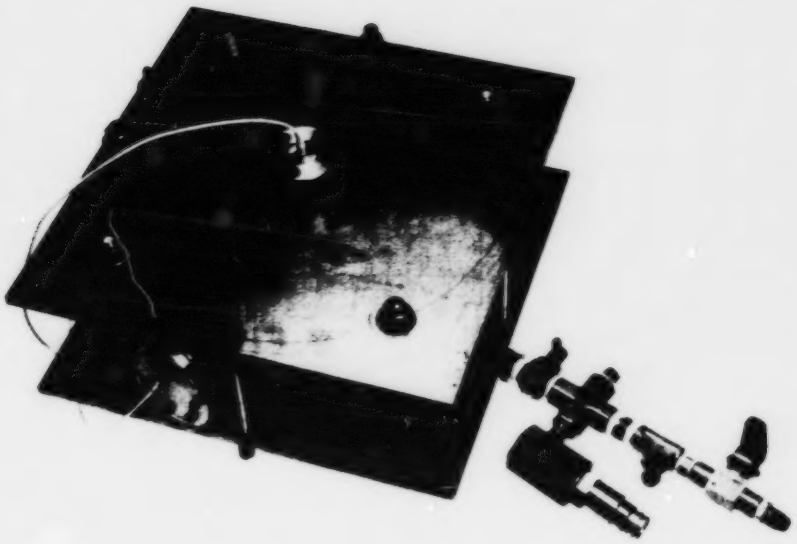


Figure 7 Hydraulic compression cell.

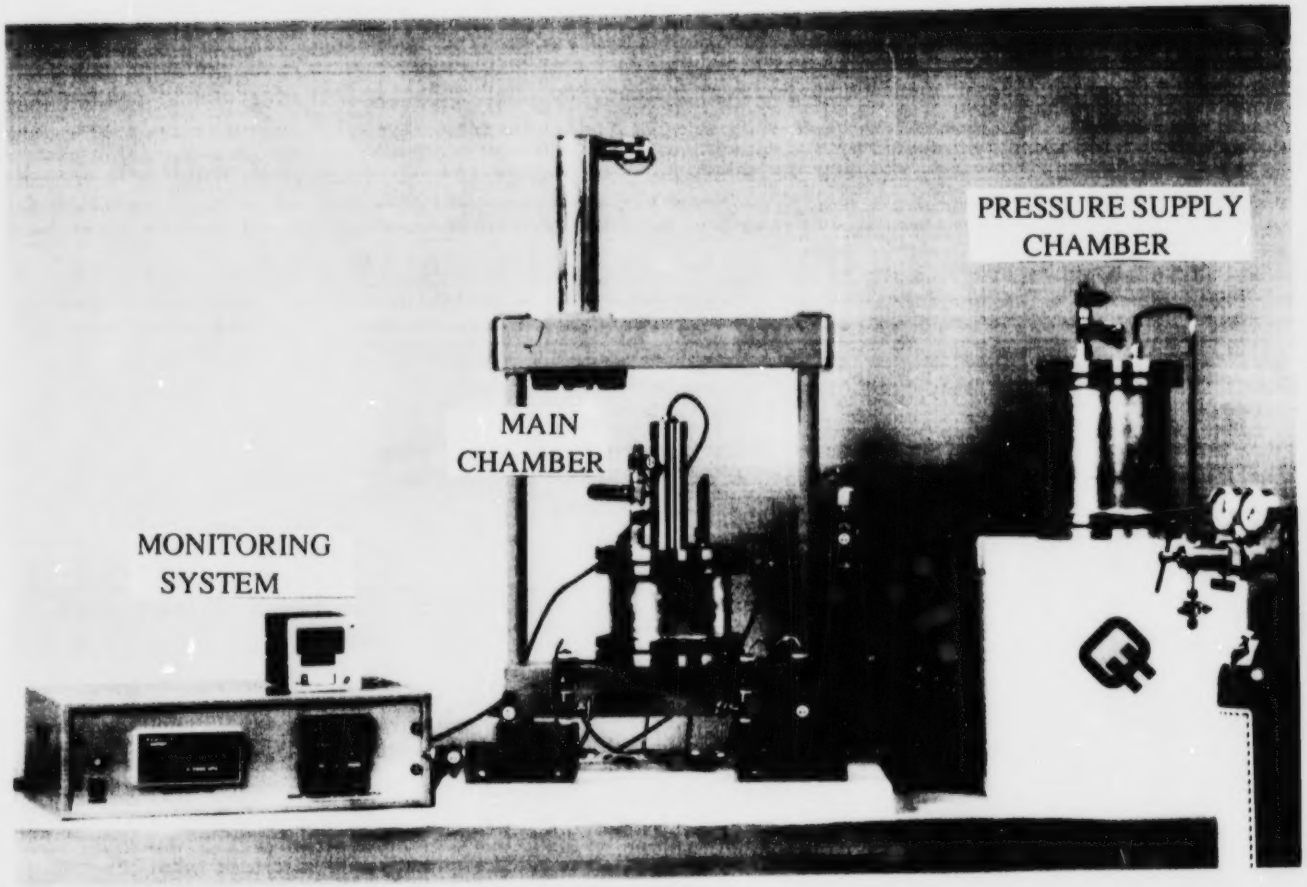


Figure 8 The high pressure compression test apparatus.

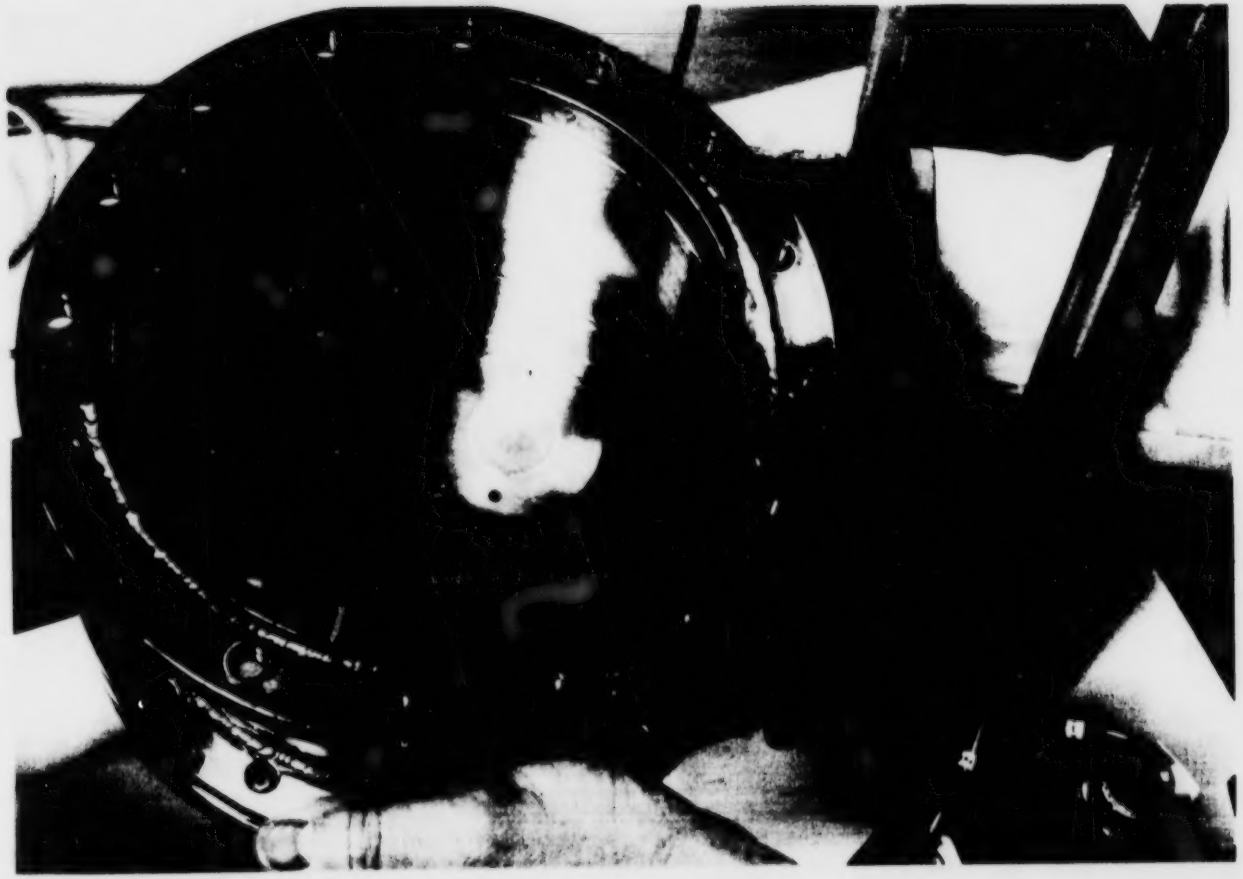


Figure 9 The steel collars welded to the top and bottom of the cylinder.

Figure 10 The relief valve, air vent and LVDT coning tower.

Figure 11 The water jet deflection assembly and the expandable c ring seal.

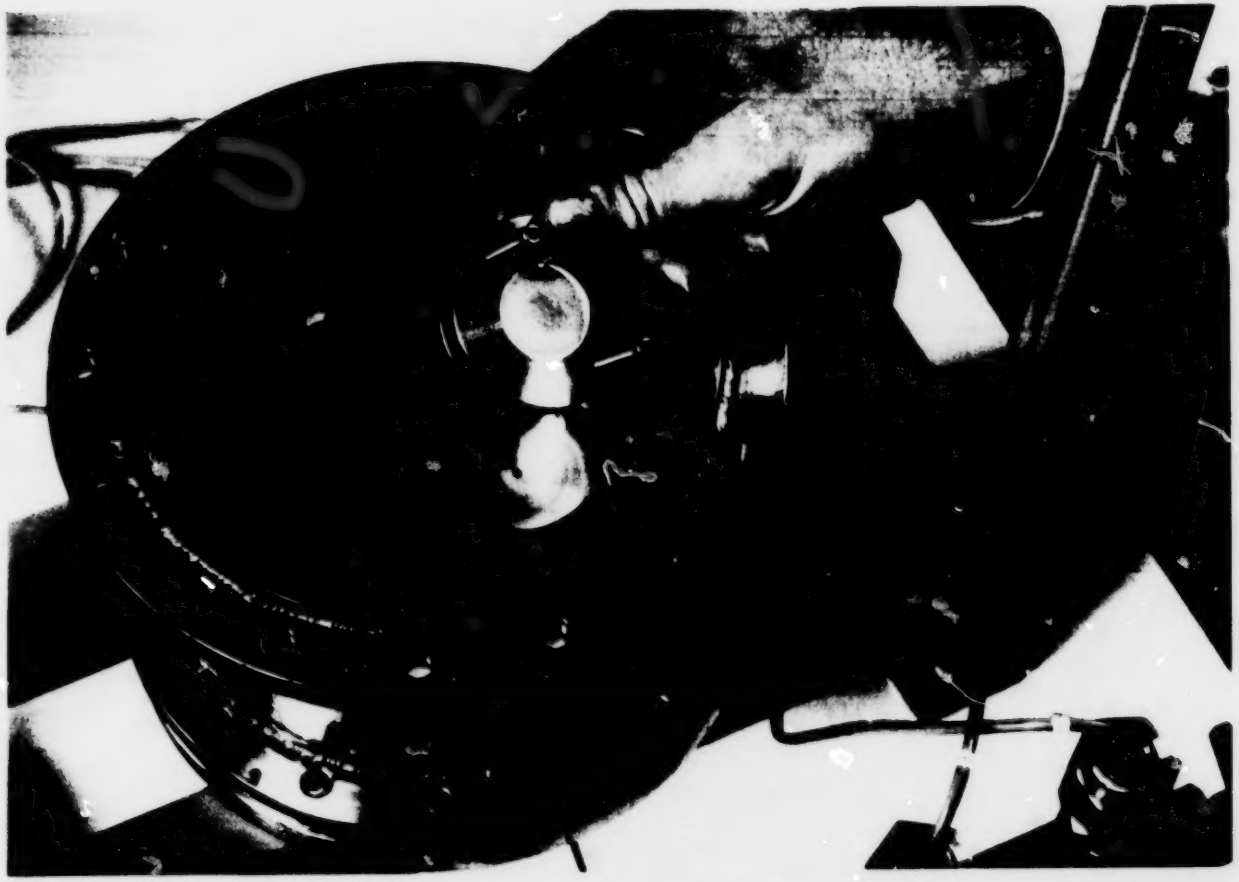


Figure 12 The porous stone assembly.

90-129

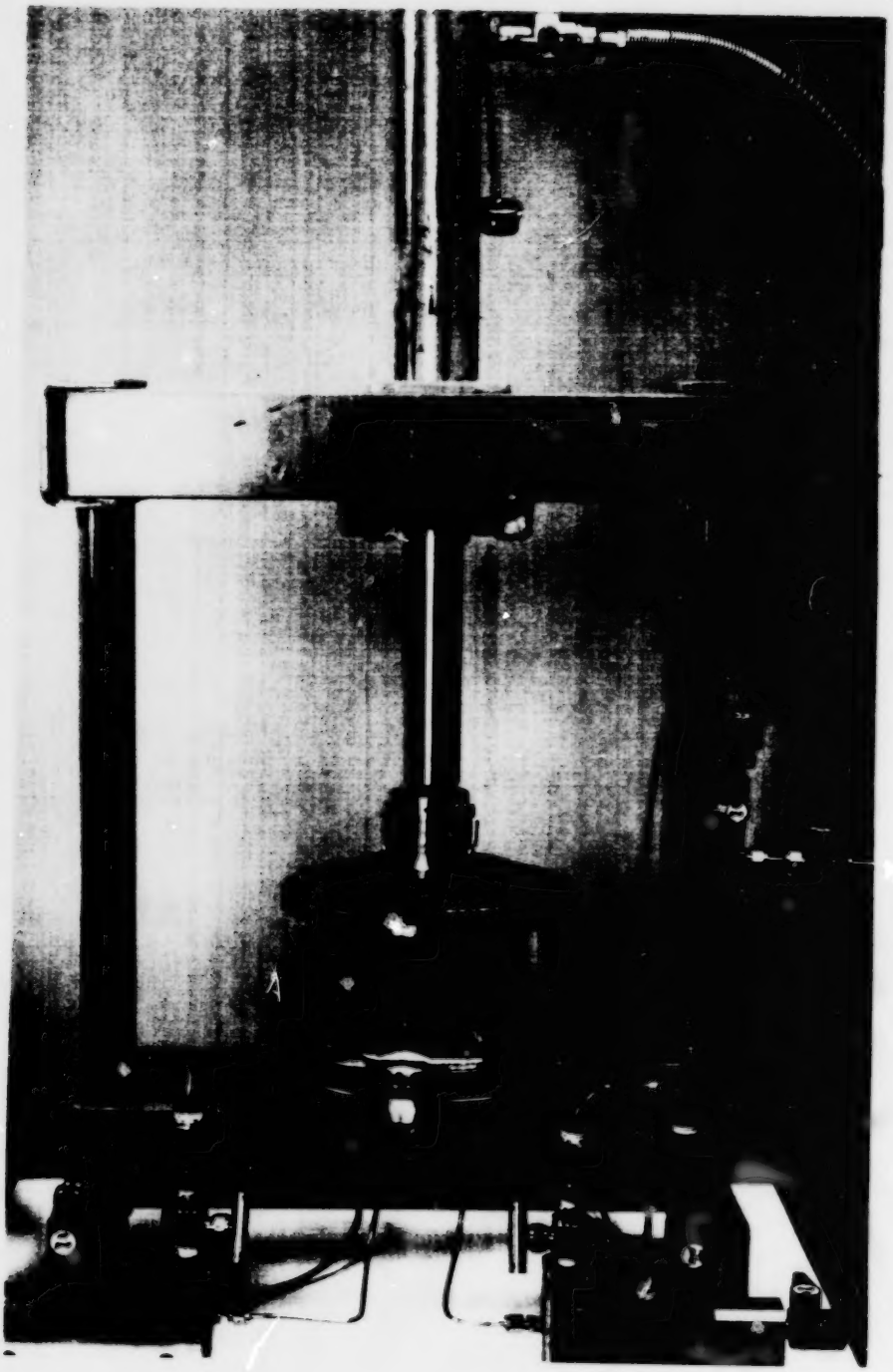


Figure 13 The pressure tranducer manifolds.

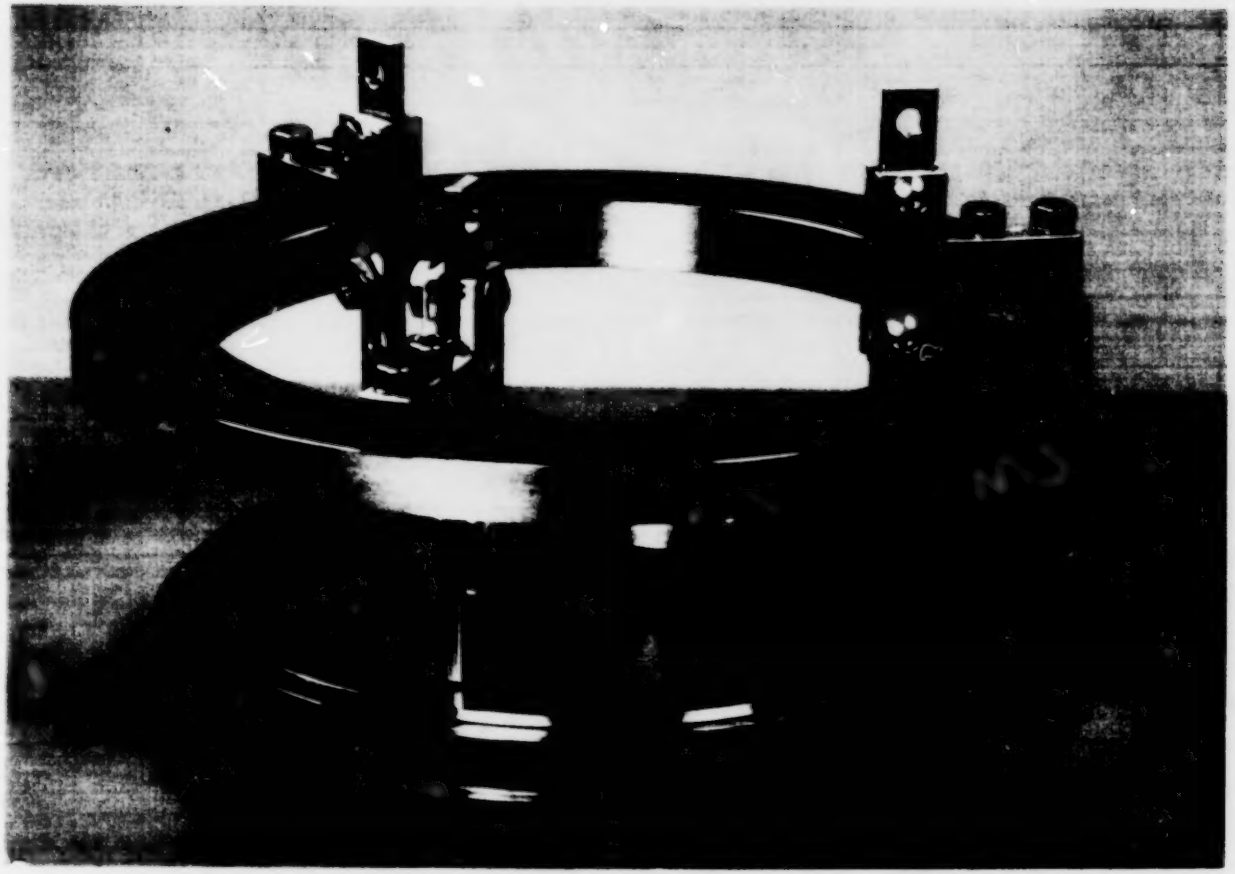


Figure 14 Special equipment designed to install the expandable o-ring seal.

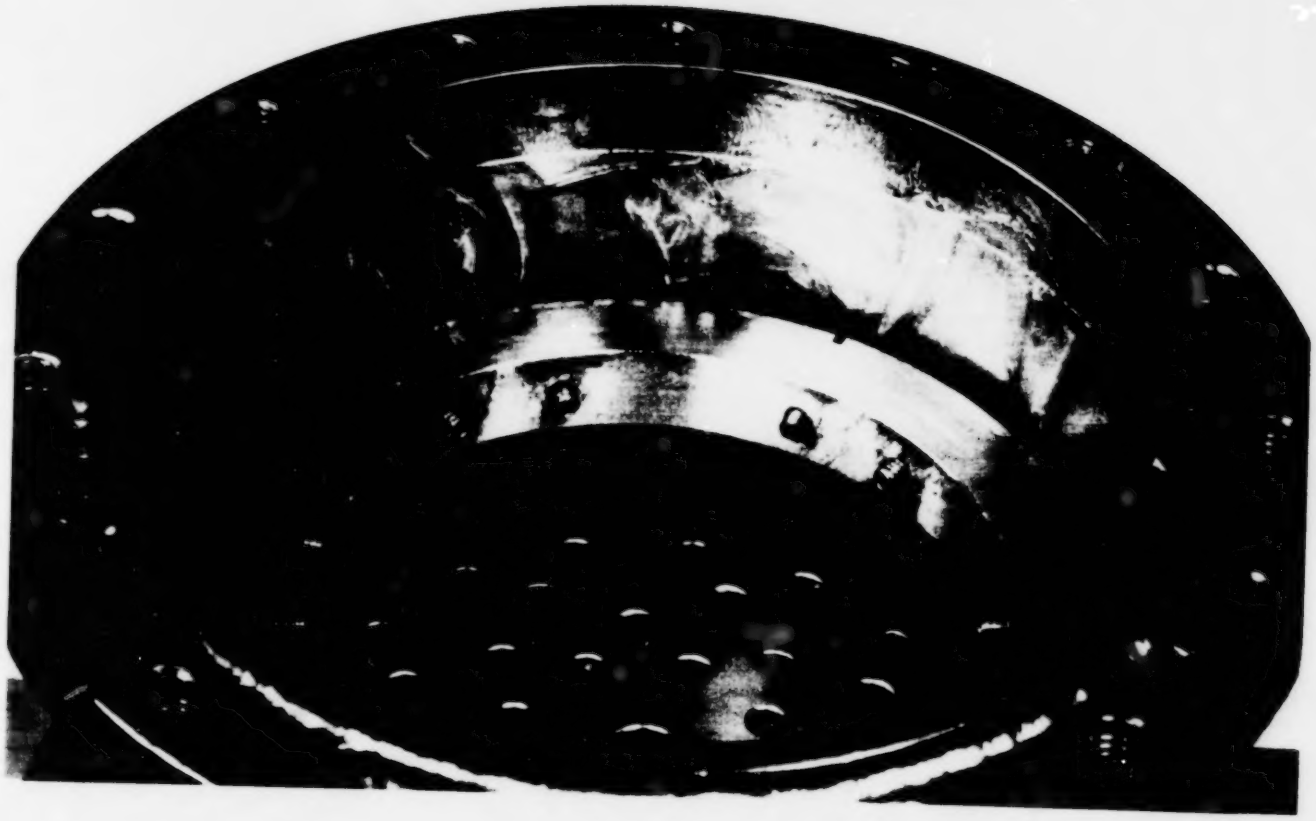


Figure 15 The main chamber sealed with the neoprene membrane and the expandable o-ring seal.

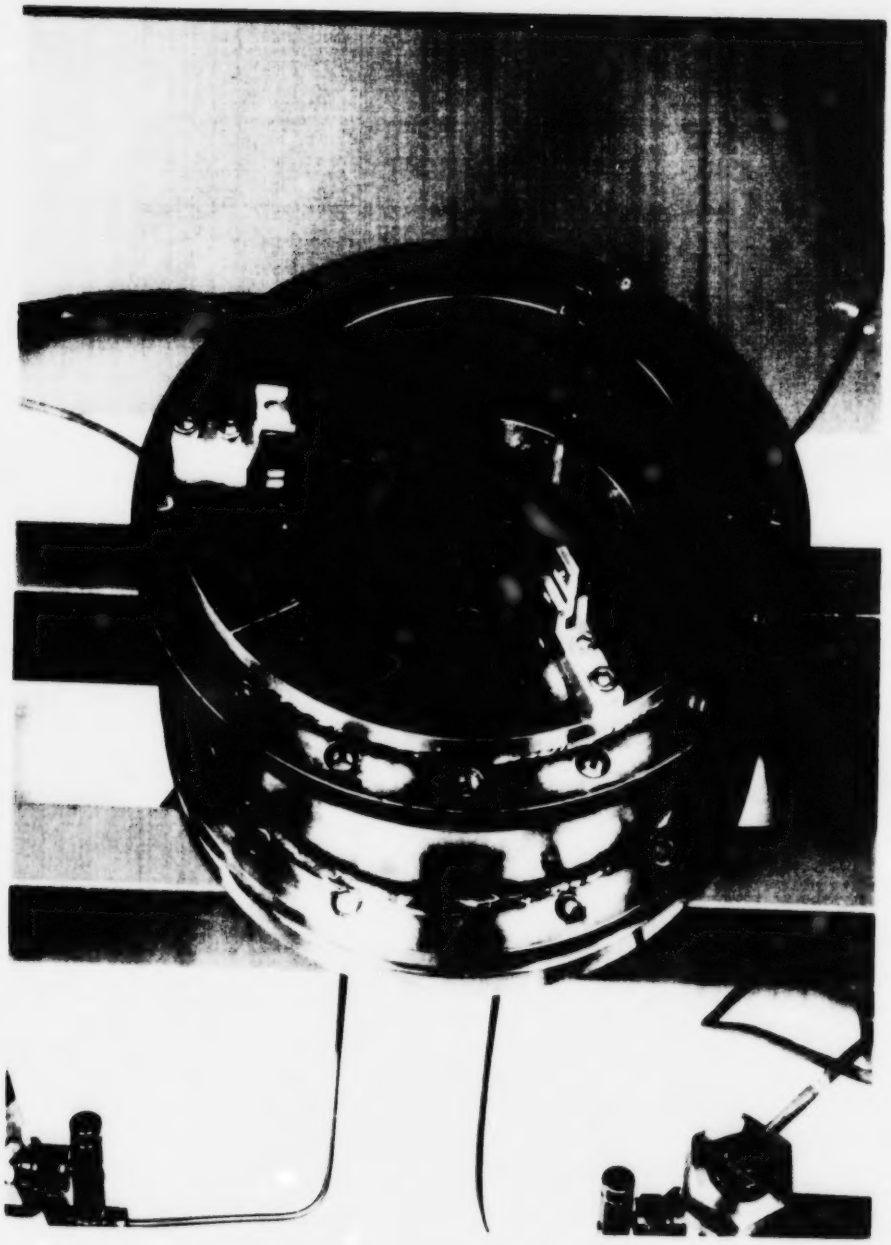


Figure 16 Installing the expandable o-ring seal.

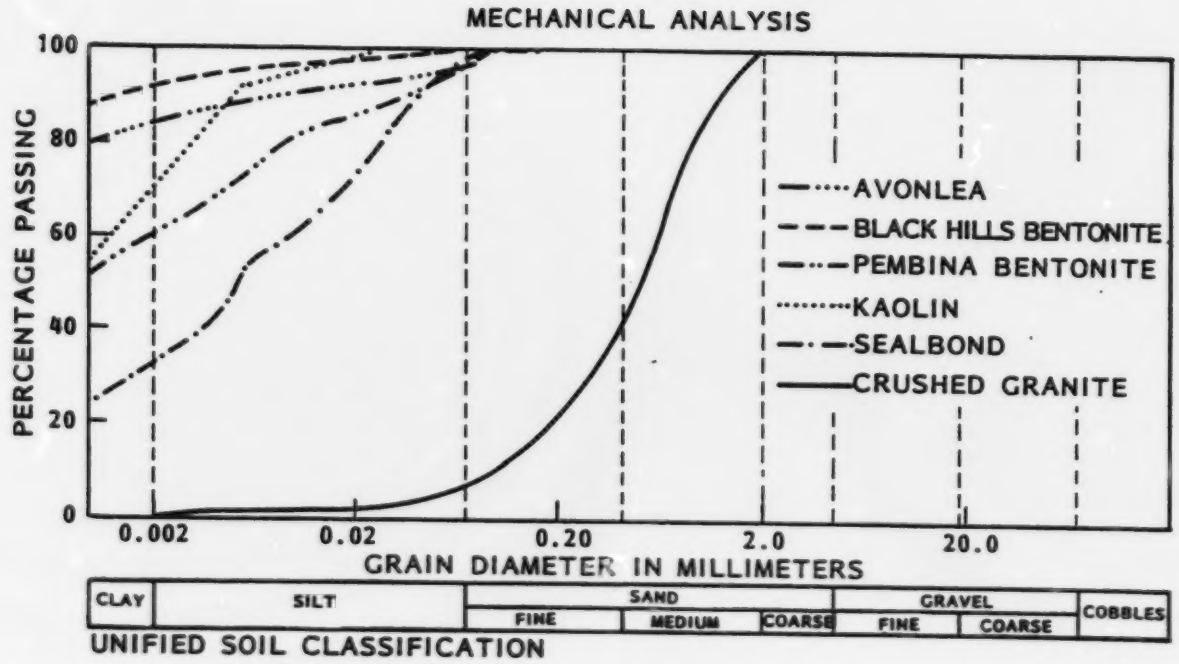


Figure 17 Particle-size-distribution curves.

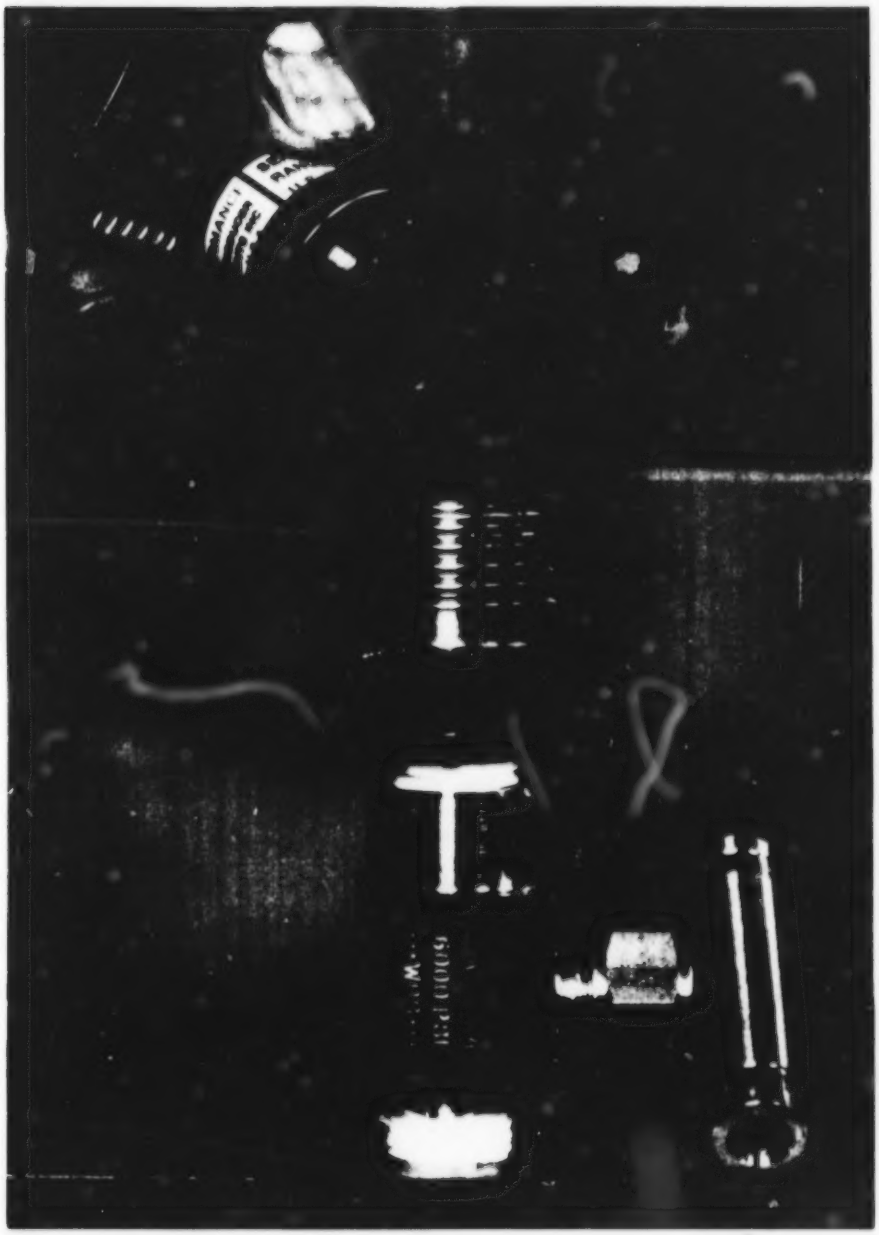


Figure 18 The pressure transducer mounting port.

Figure 19 Placement of sample in the main chamber.

Figure 20 Placement of the steel platen.

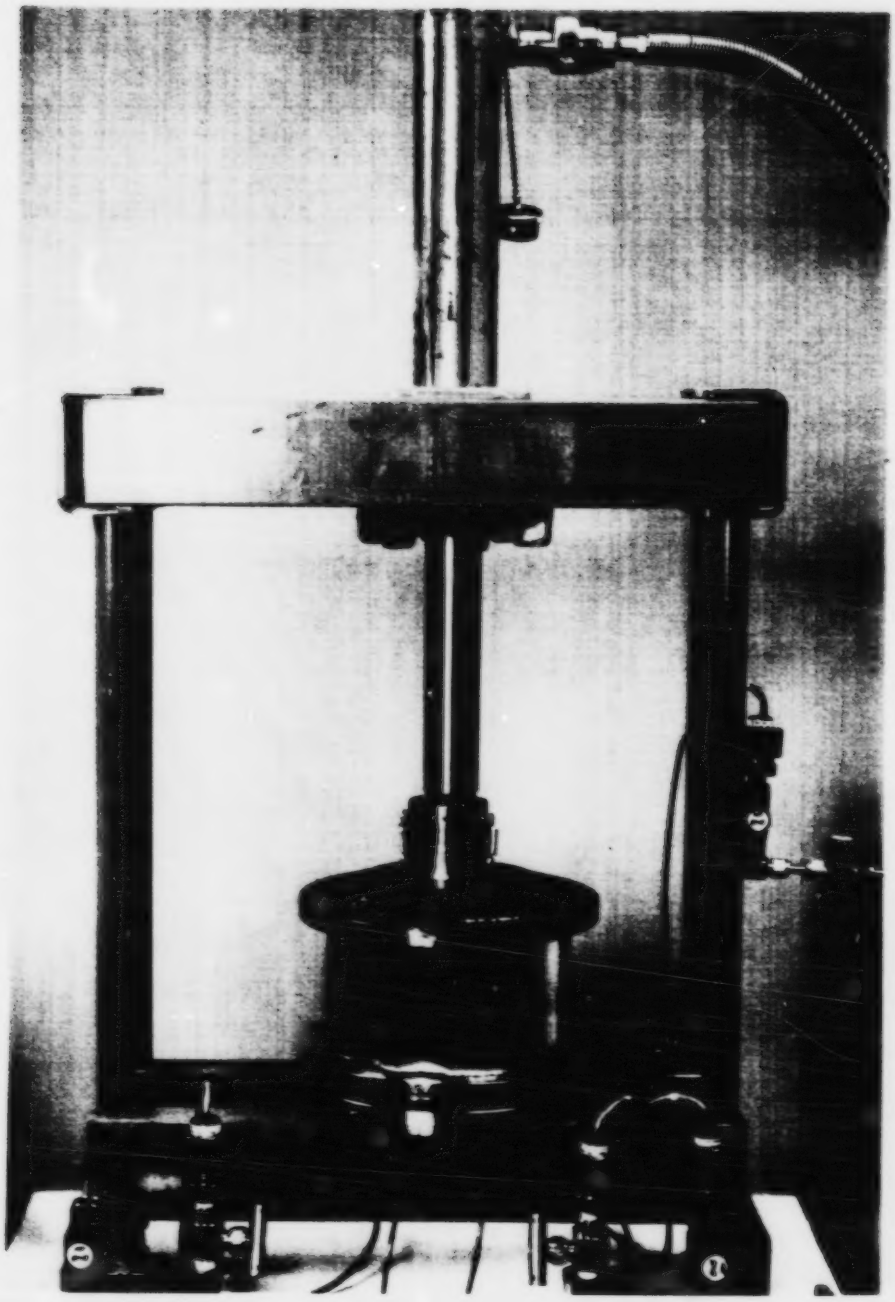


Figure 21 Static compaction of the backfill specimen.

Figure 22 Installation of the LVDT.

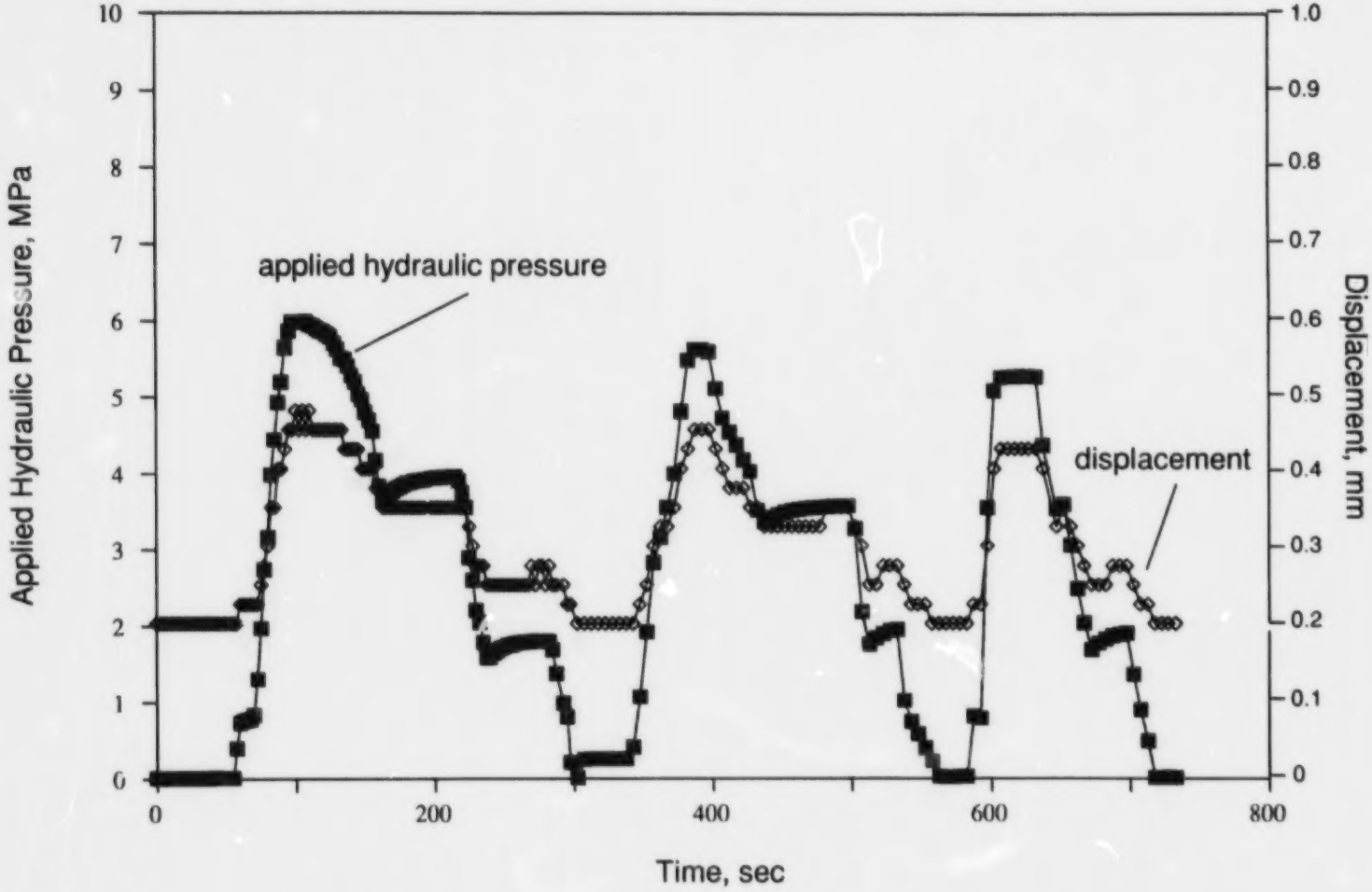


Figure 23 The elastic vertical deformation of the main chamber vs. applied hydraulic pressure - calibration test.

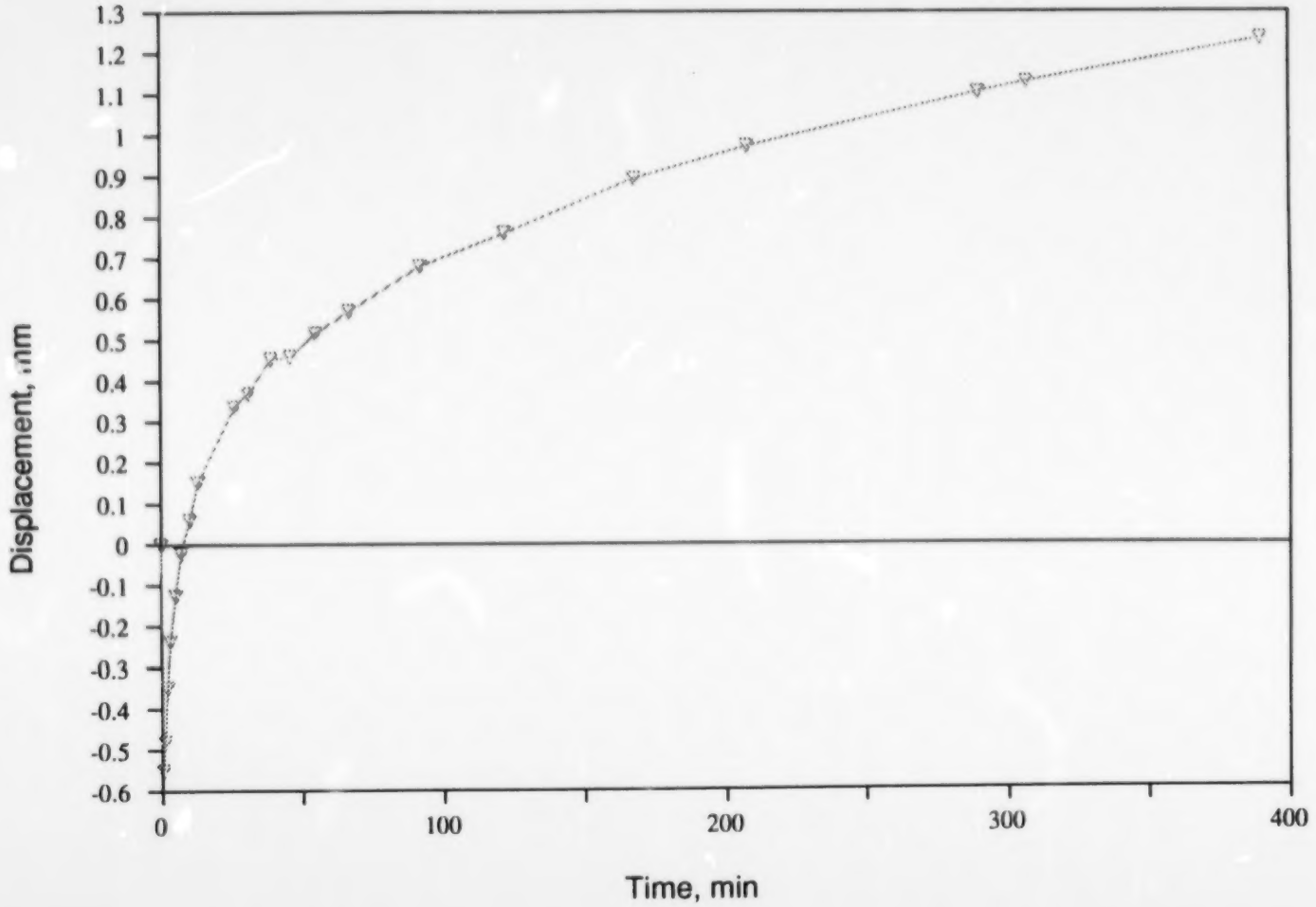


Figure 24 Displacement vs. time - swelling-type backfill specimen.

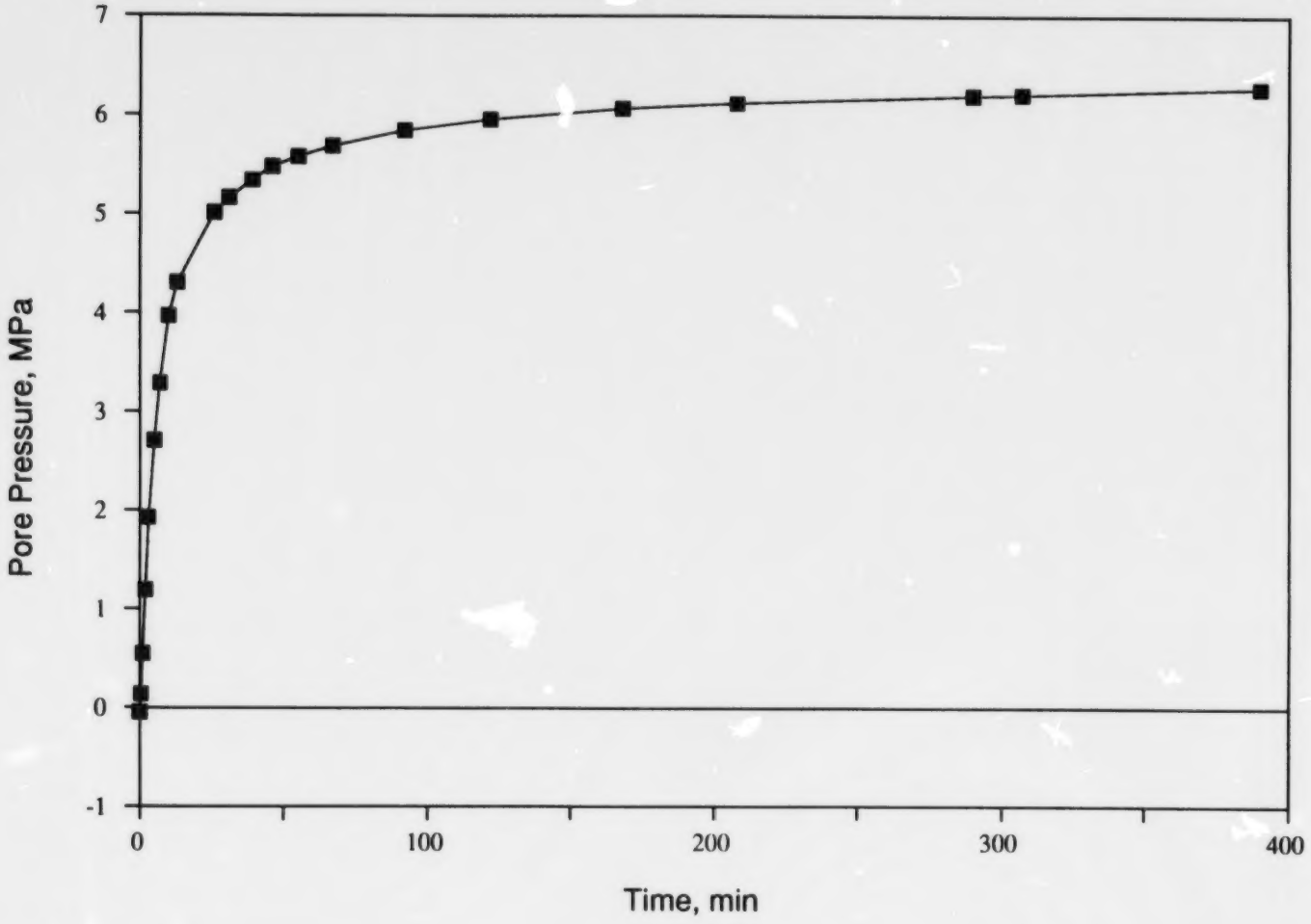


Figure 25 Pore pressure vs. time - swelling-type backfill specimen.

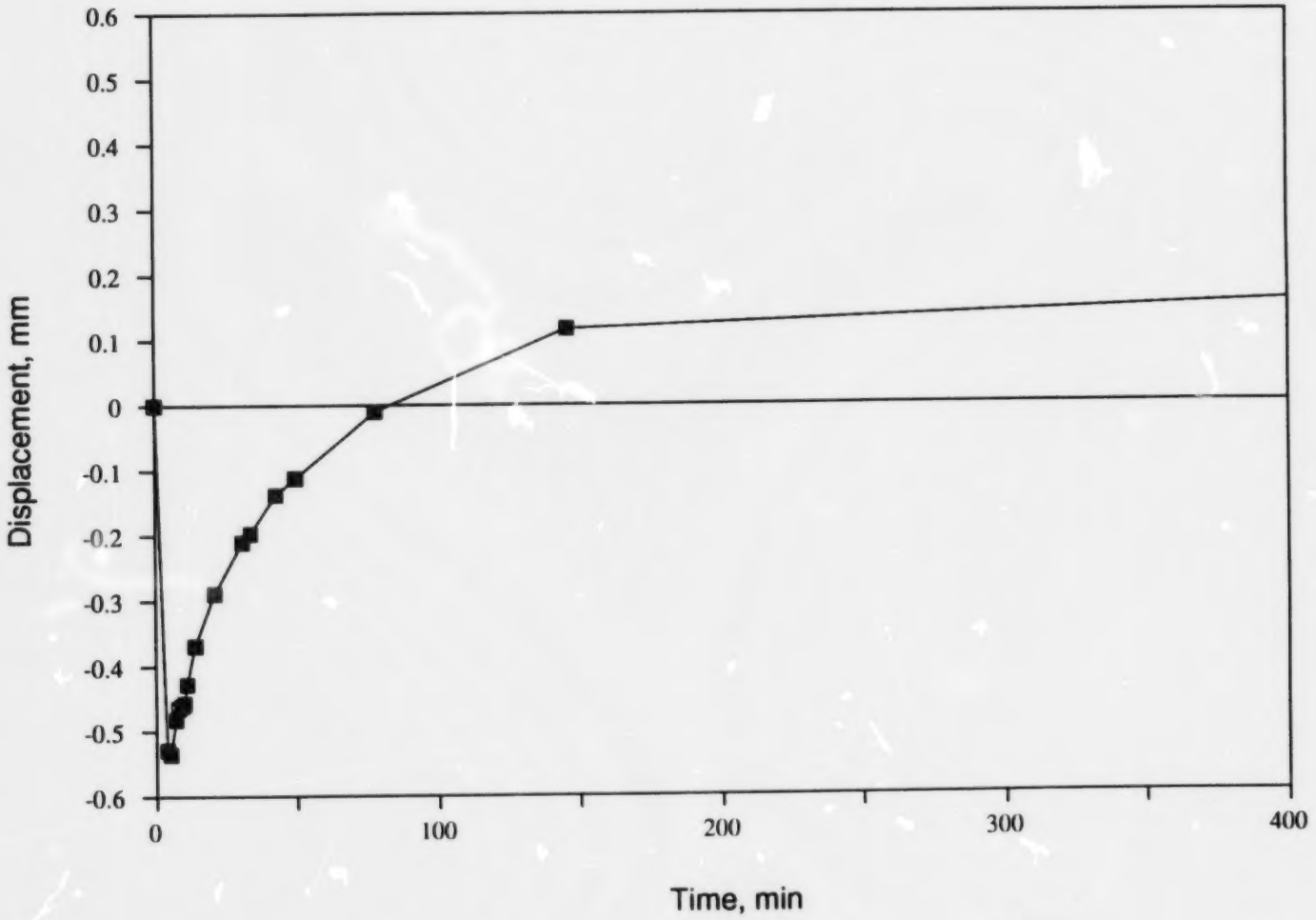


Figure 26 Displacement vs. time - Nonswelling-type backfill specimen.

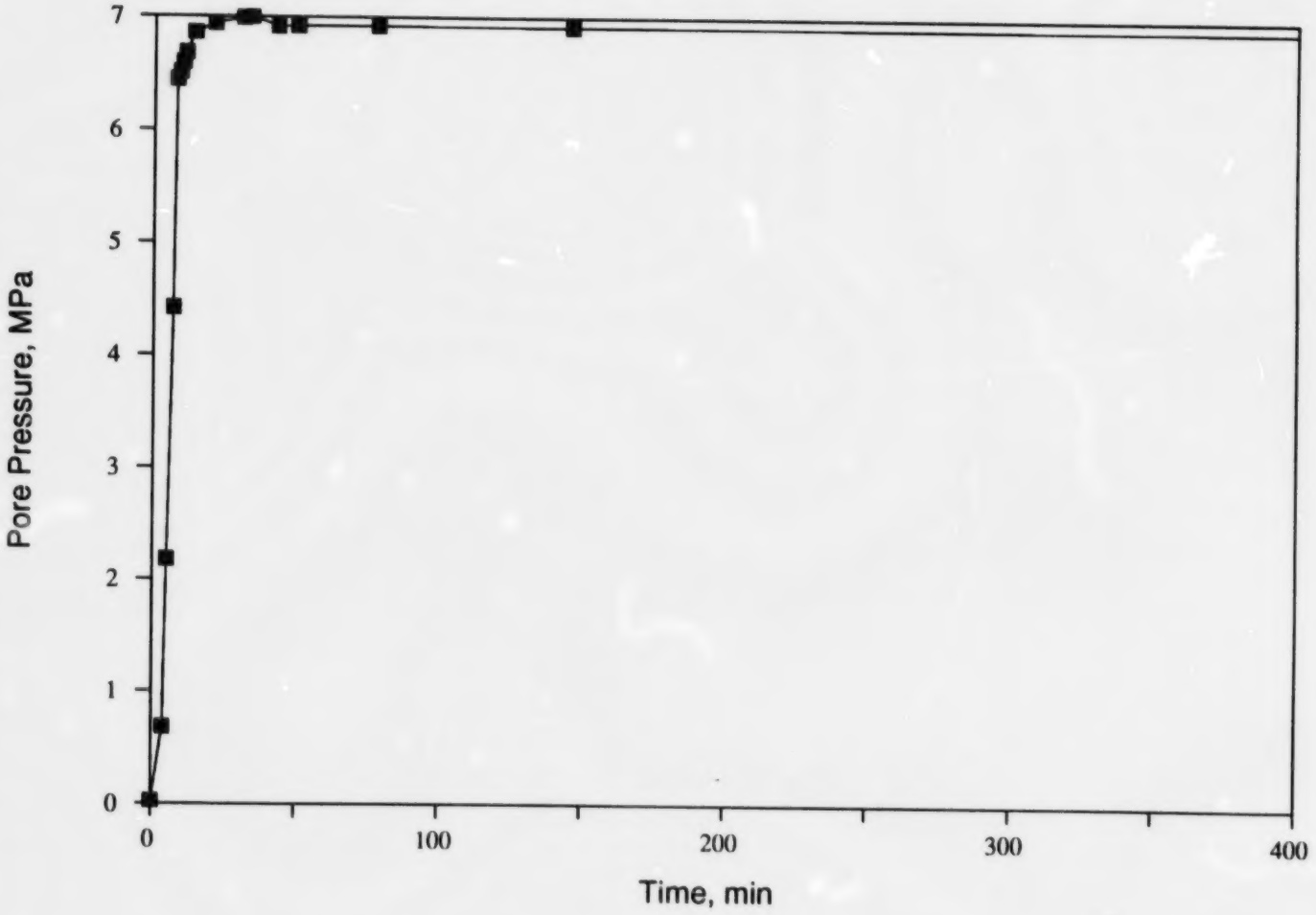


Figure 27 Pore pressure vs. time - Nonswelling-type backfill specimen.

APPENDIX A

(Drawings prepared by Mr. N. Miura of the
Mechanical Research Department,
Ontario Hydro Research Division)

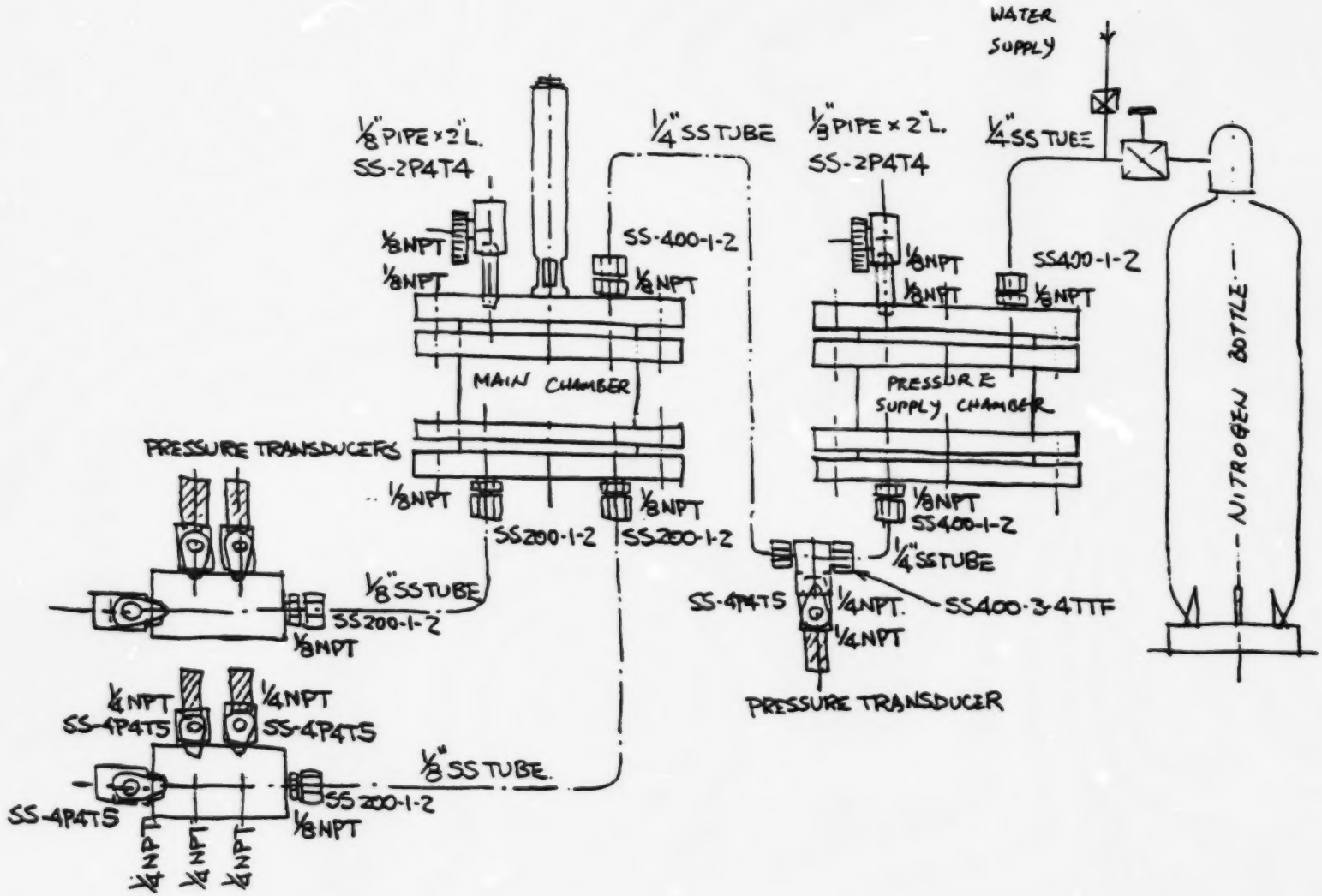


Figure A-1 Layout of the equipment.

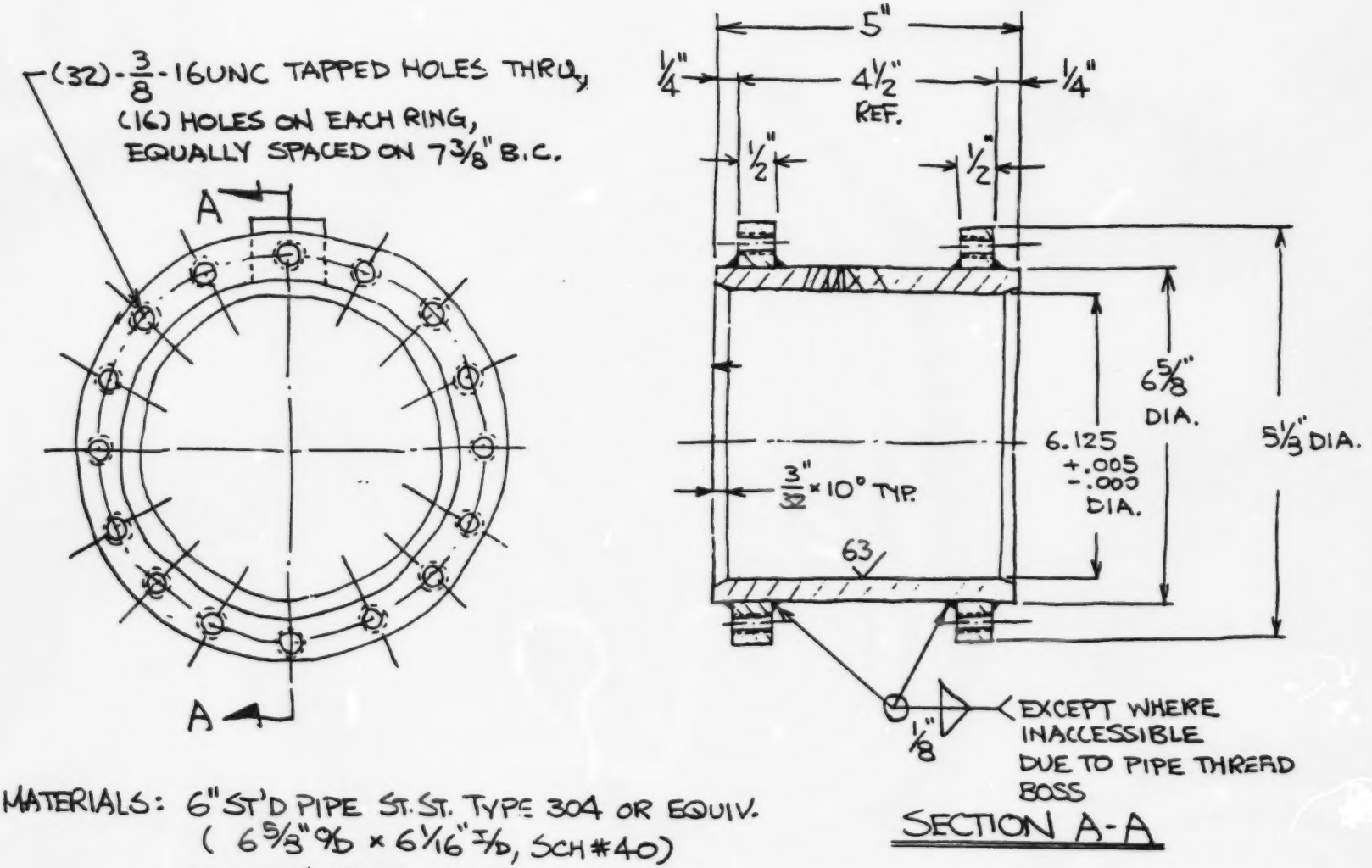
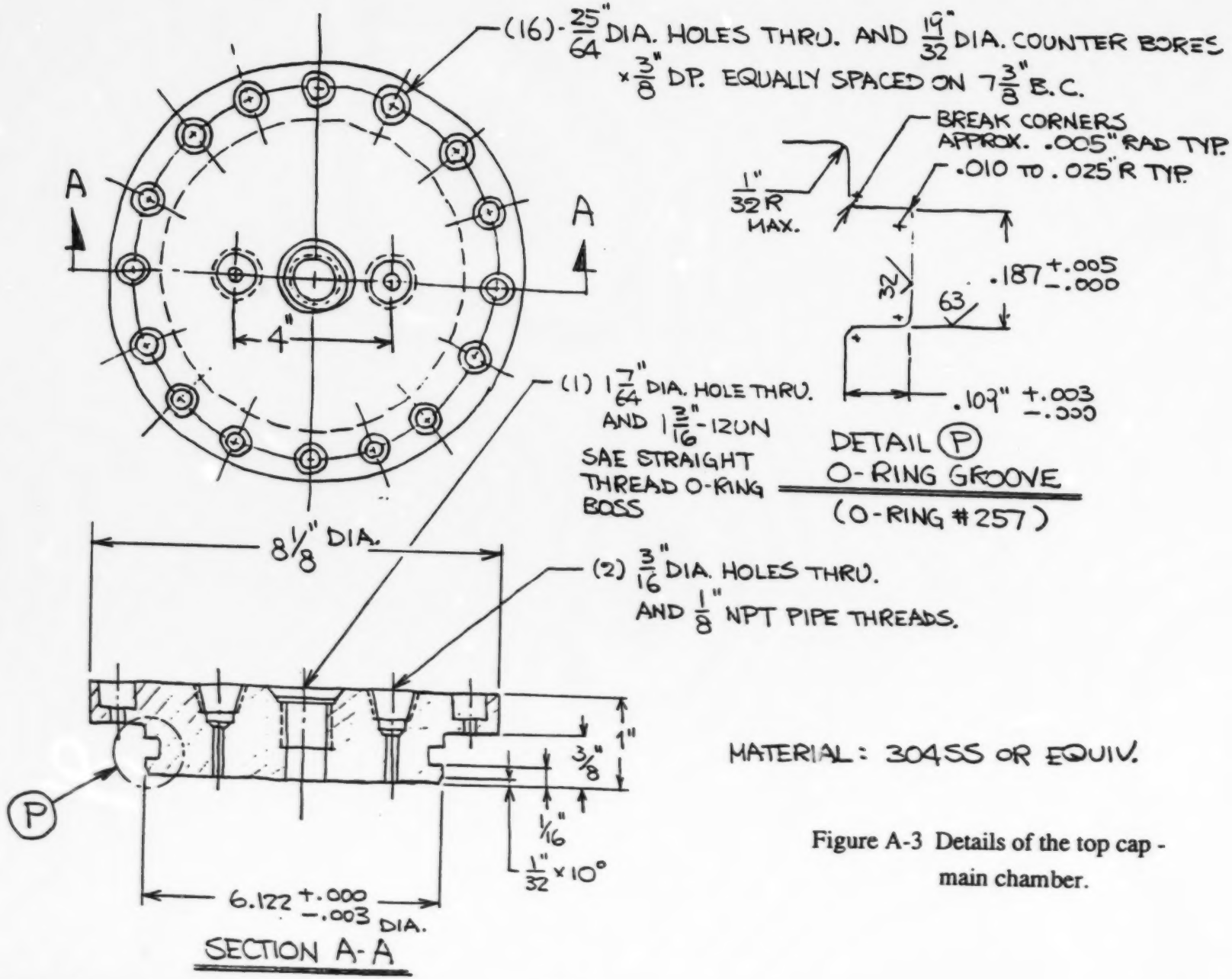


Figure A-2 Details of the main chamber.



MATERIAL: 304SS OR EQUIV.

Figure A-3 Details of the top cap - main chamber.

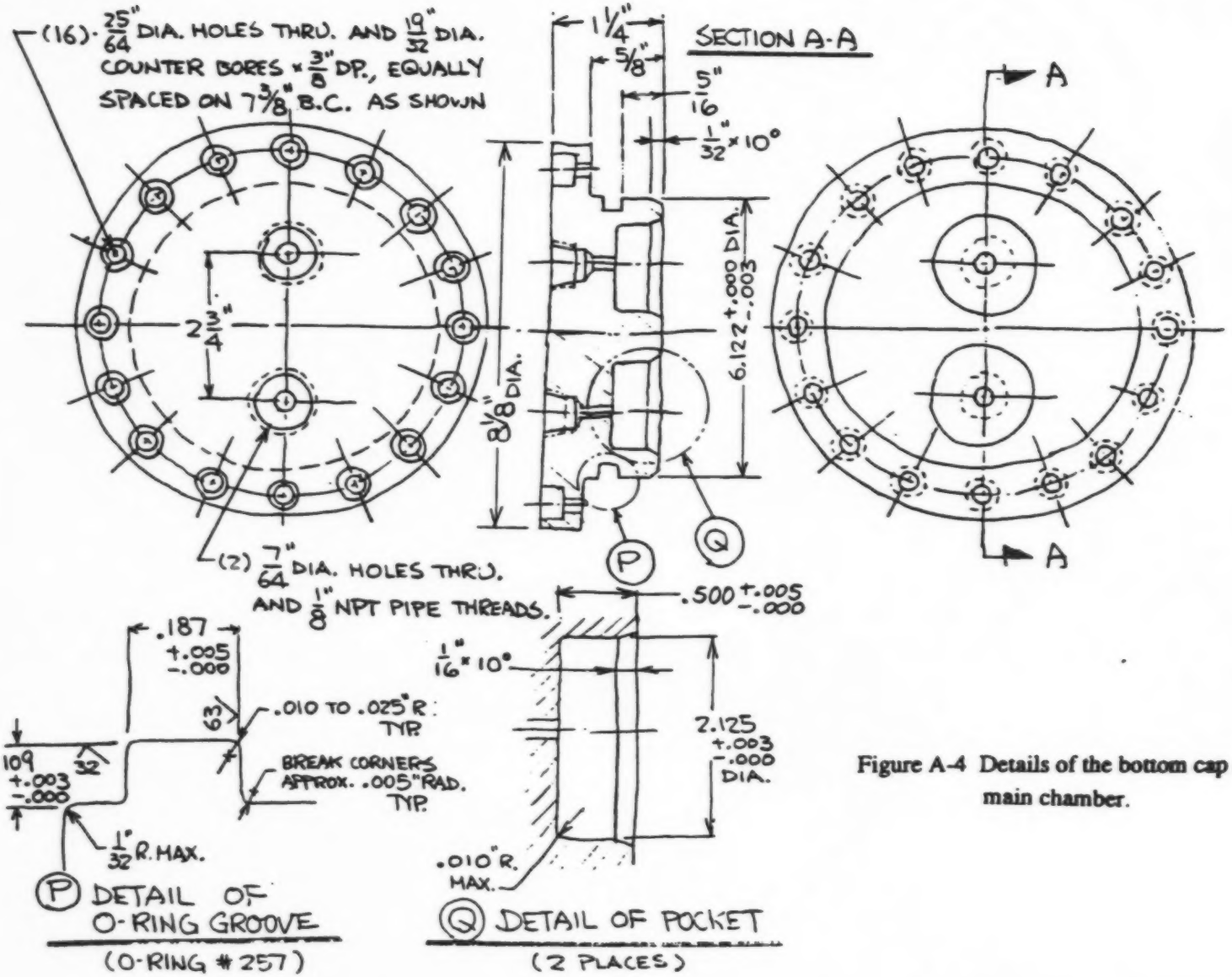


Figure A-4 Details of the bottom cap - main chamber.

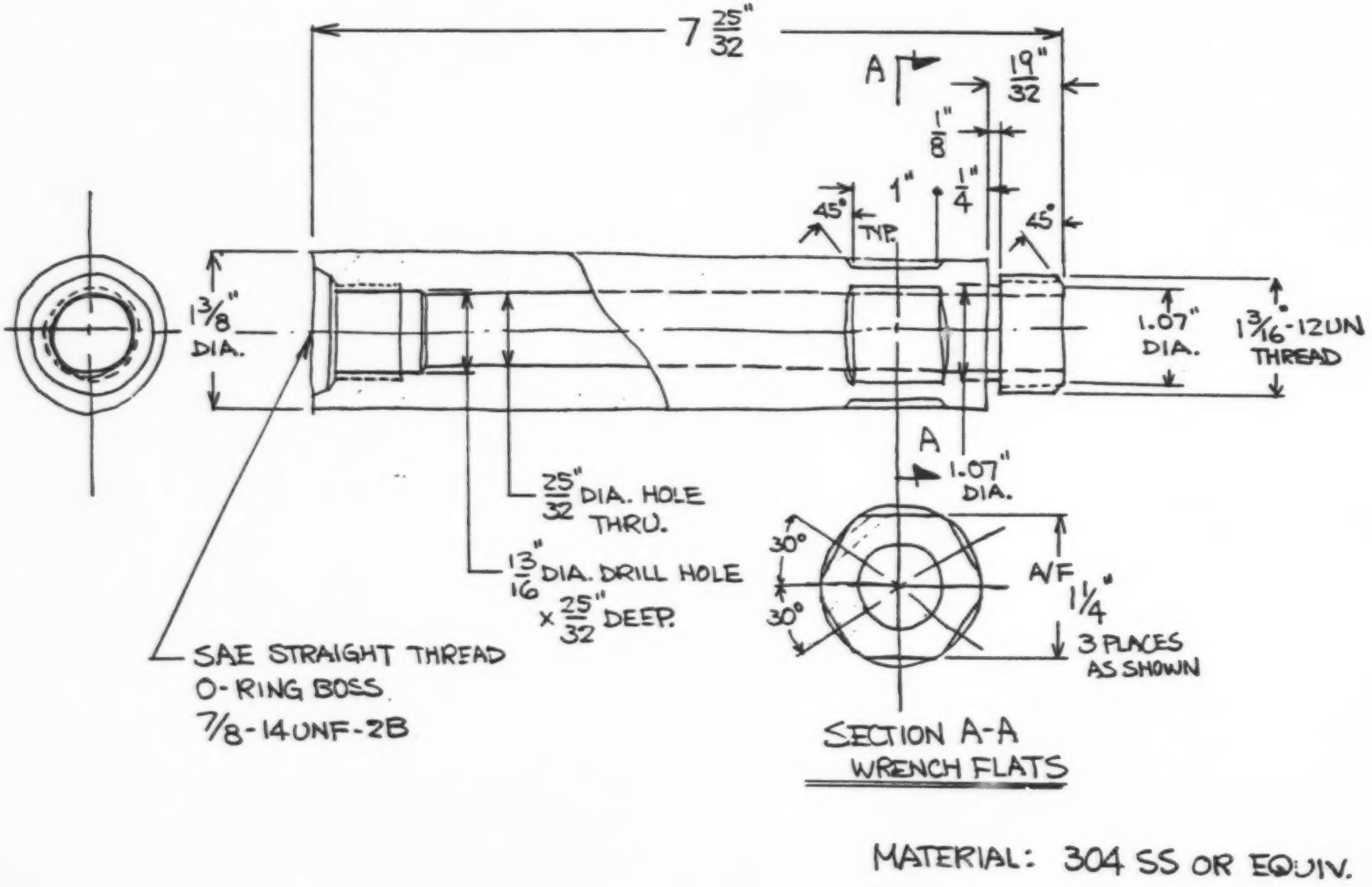


Figure A-5 Design of the LVDT coning tower.

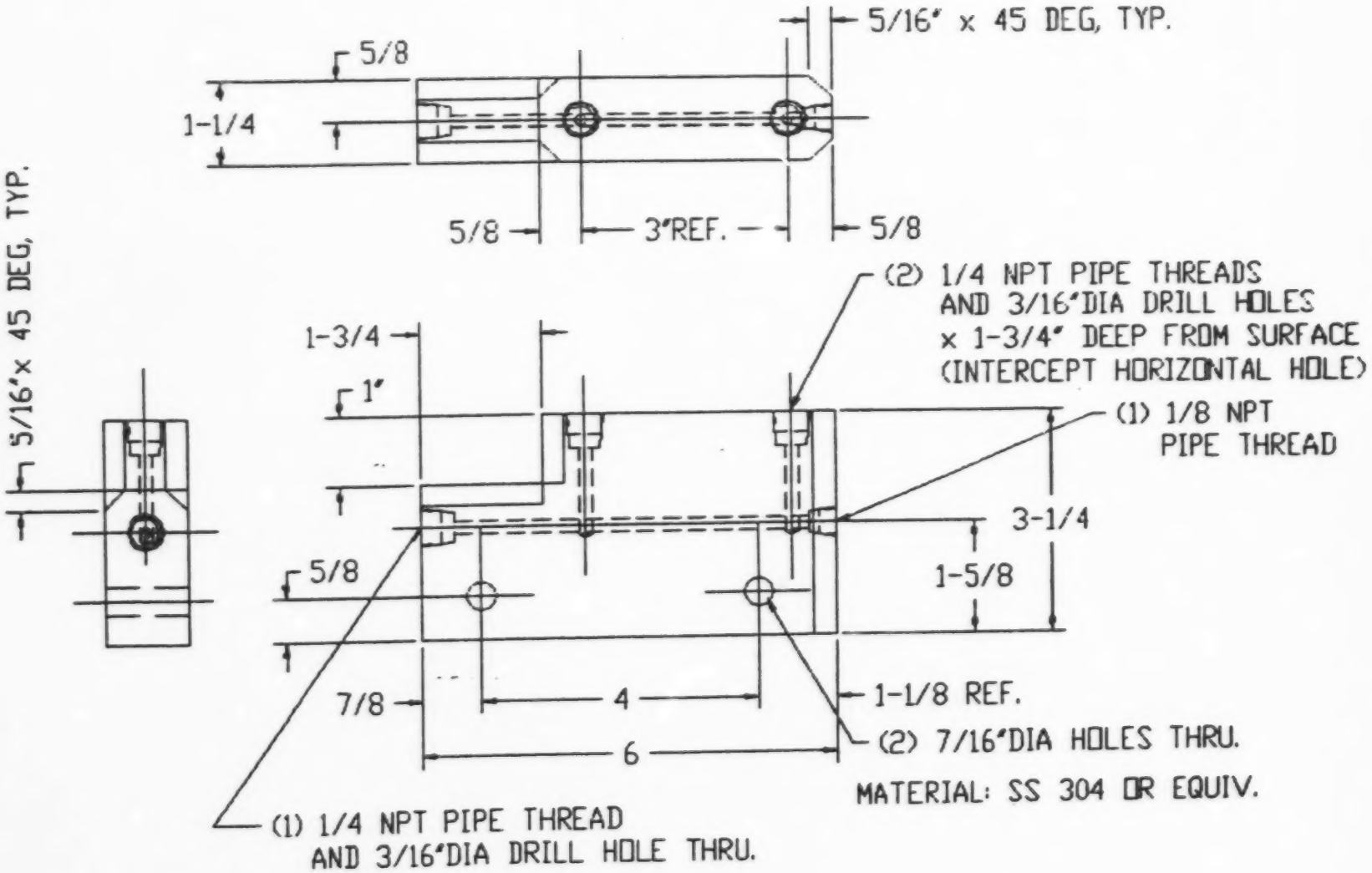


Figure A-6 Details of the pressure tranducer manifold.

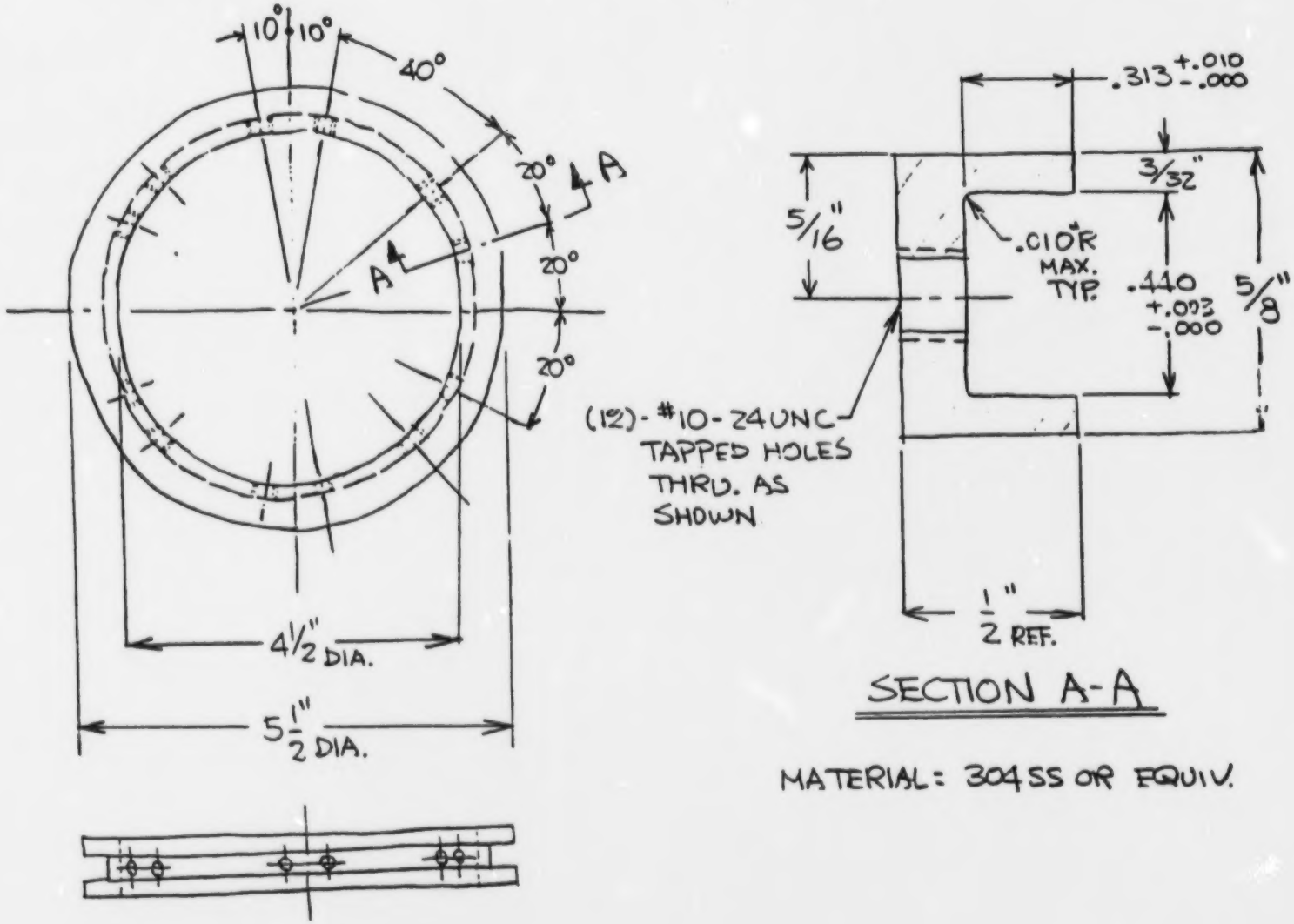


Figure A-7 Details of the expandable ring.

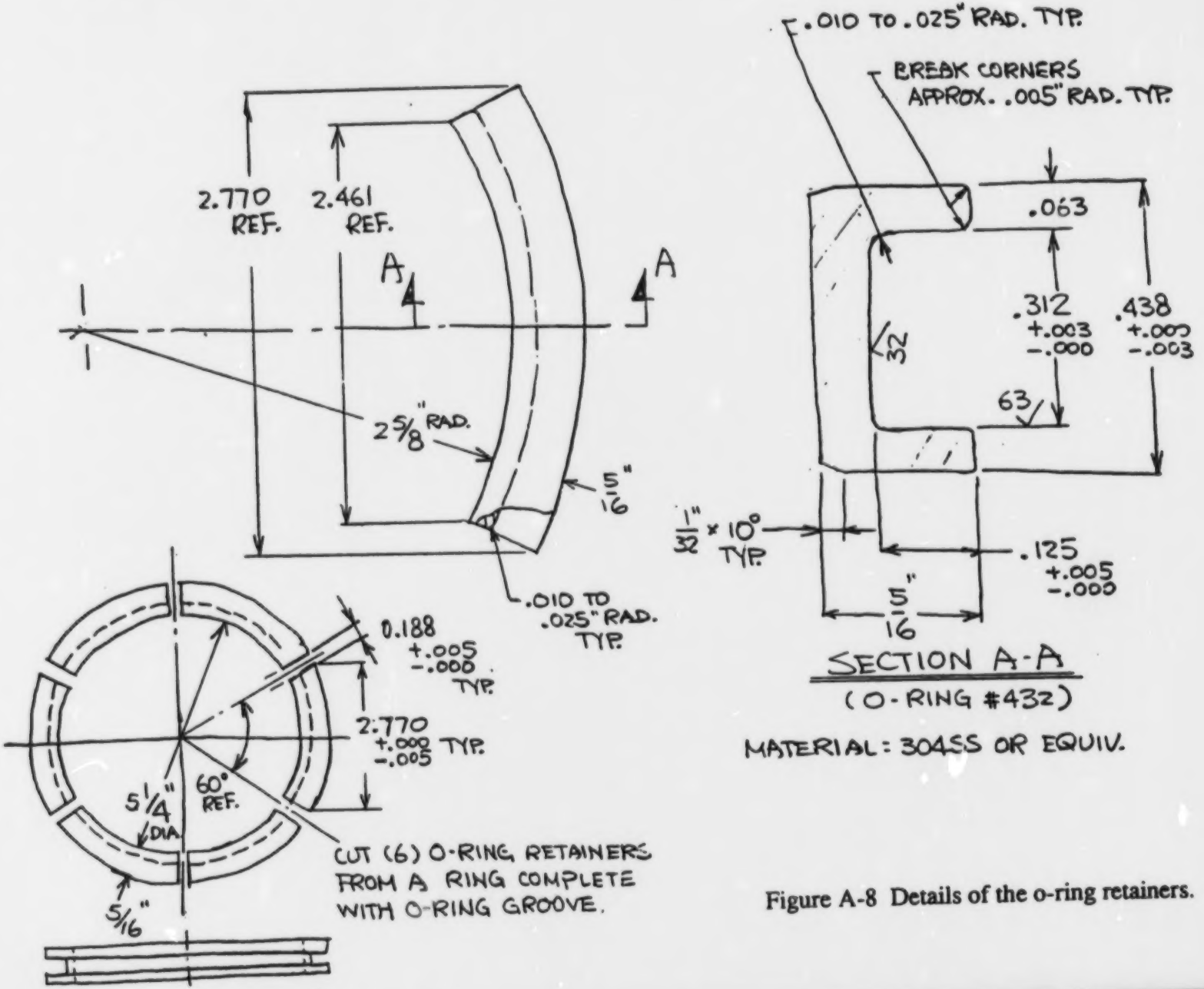
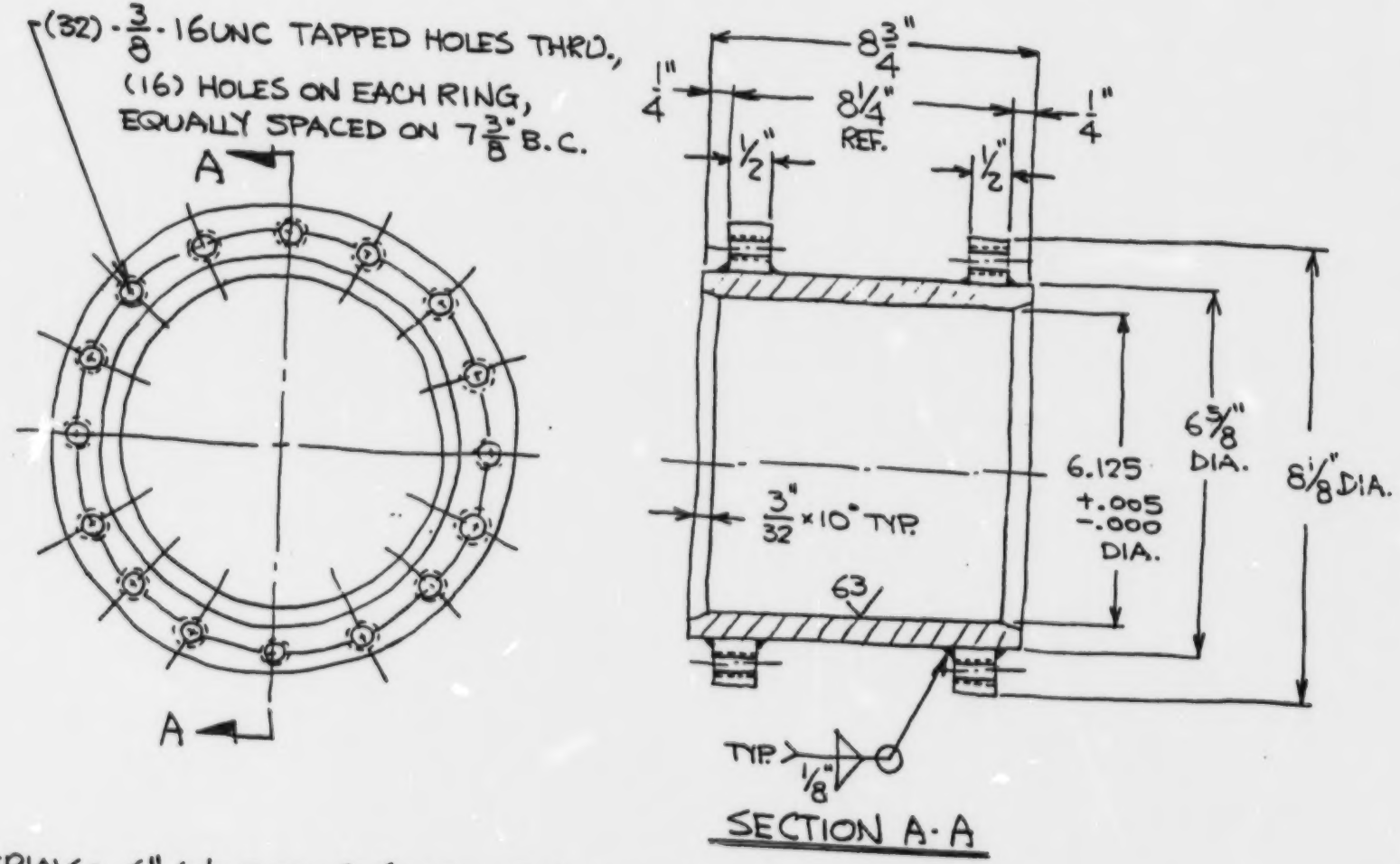
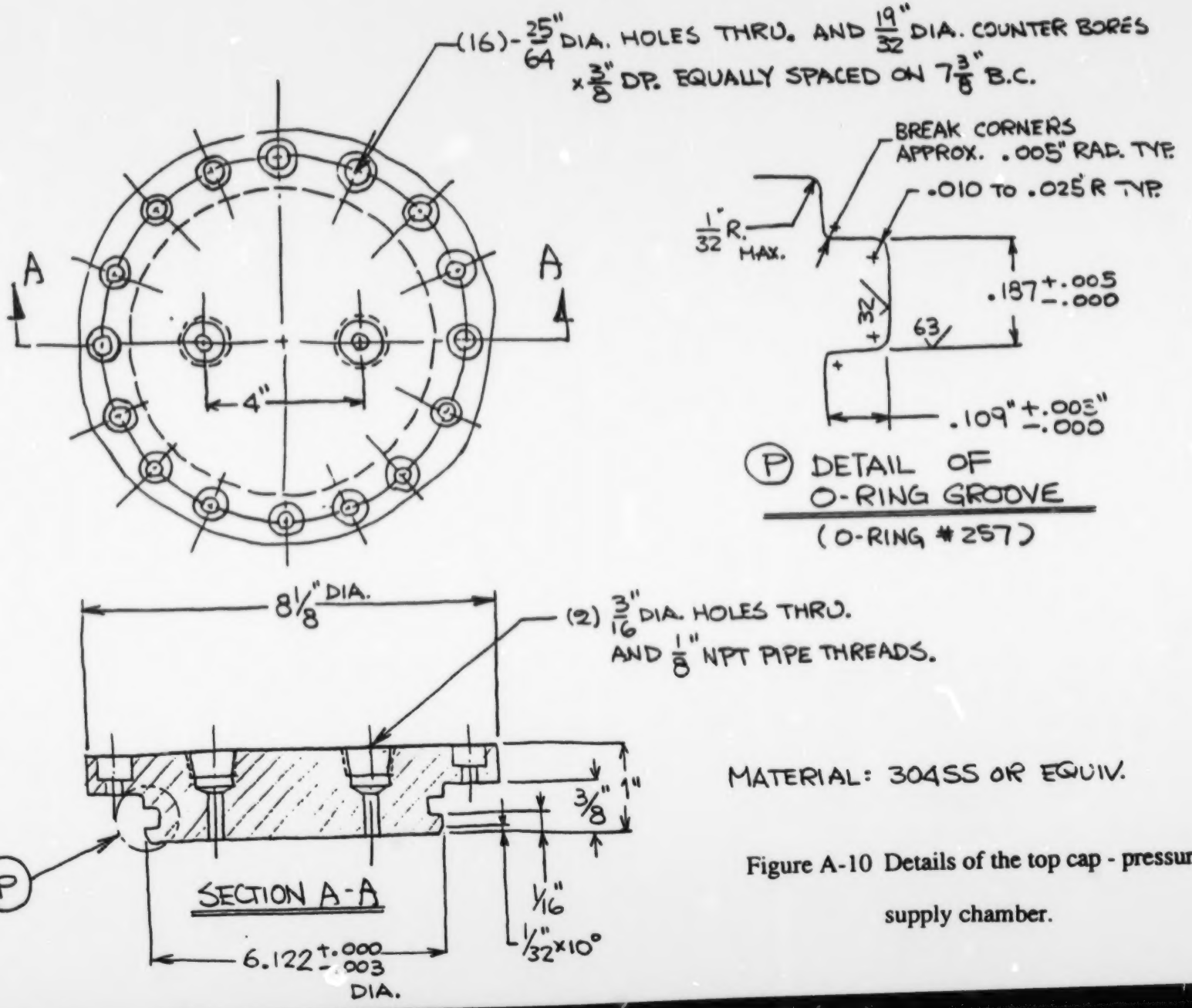


Figure A-8 Details of the o-ring retainers.



MATERIALS: 6" ST'D PIPE ST. ST. TYPE 304 OR EQUIV.
(6 5/8" O/D x 6 1/16" I/D, SCH #40)
AND 304 ST. ST. OR EQUIV. (RINGS)

Figure A-9 Details of the pressure supply chamber.



MATERIAL: 304SS OR EQUIV.

Figure A-10 Details of the top cap - pressure supply chamber.

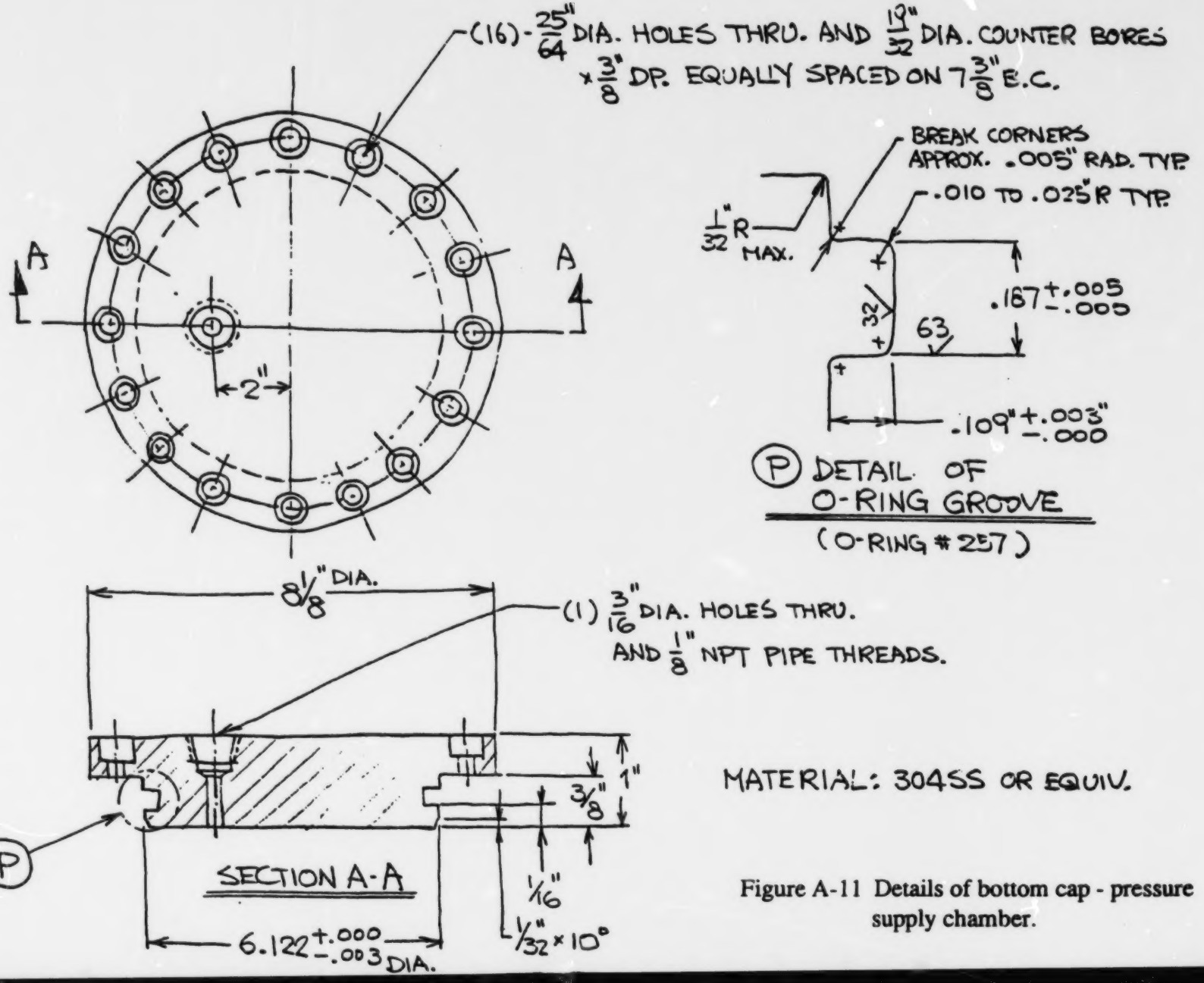


Figure A-11 Details of bottom cap - pressure supply chamber.